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PROJECT APOLLO

# VERIFICATION OF ENTRY MONITOR SYSTEM LINE PATTERNS

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## TABLE OF CONTENTS

# TABLES

Table

## FIGURES

Figure

FIGURES (Continued)

FIGURES (Concluded)

# SUMMARY

An examination has been conducted of procedures and data which relate to the derivation of the EMS (entry monitor system) flight limit lines and range guidelines for the two types of lunar return scroll patterns (3500 n mi and non-exit). All derivation procedures were found to conform to those presented in North American Rockwell document SD68-146, "Entry Monitor System (EMS) Flight Pattern Limit Line Generation and Development Procedures," (reference 1). Data were checked to insure consistency throughout the development of each set of lines. One error was found in the development of the 75 n mi range guideline. The error caused this guideline to represent a range incorrect by two to four nautical miles for levels of G between G = 2.5 and G = 3.0, and between G = 7.0 and G = 8.0. In an actual entry, this small error would be accounted for as the 50 n mi range guideline, which was correctly derived, was approached so that the error did not represent a serious compromise with the EMS backup ranging capability. No other errors or inconsistencies were found. It was concluded that the flight limit lines and the range guidelines, with the one exception mentioned above, were correctly developed and were valid for all applicable flight conditions for Apollo entries.

# INTRODUCTION

The terminal phase of all Apollo missions will be that phase in which the CM (command module) and its three crewmen safely enter the earth's atmosphere and range to a preselected target. The PGNCS (primary guidance, navigation, and control system) of the CM can provide automatic execution of all vehicle maneuvers. There is a possibility, however, that the PGNCS could malfunction in such a way as to endanger crew safety. The malfunction of the PGNCS can be considered to be either of two general types.

The first type of malfunction is one which is discernible to the crew in some manner such as a lighting of the master alarm light. When this type of malfunction occurs, the crew can immediately assume manual control of the spacecraft and can complete the entry according to some predetermined backup procedure. A second type of malfunction is one which does not result in a warning to the crew and is one which causes PGNCS to issue erroneous control commands.

At nearly any time in an entry, erroneous control commands could cause the occurrence of flight conditions for which no recovery maneuver would protect the crew from experiencing dangerous and possibly catastrophic flight conditions. For example, early in an entry, erroneous commands could cause the acceleration loading to be increasing so rapidly that rolling to and holding the lift vector full-up would not protect the crew from experiencing very high levels of G. Erroneous commands also could

cause the altitude of the CM to be increasing so rapidly that the full lift down capability of the vehicle would not prevent a skip from the atmosphere at supercircular velocity. Therefore, the possibility of erroneous steering commands makes it imperative that PGNCS operation during entry be monitored in some manner.

The EMS accomplishes its monitoring function by displaying to the crew vehicle flight conditions and sets of limiting flight conditions beyond which the recovery capability of the CM could be insufficient to protect the crew. The sets of limiting flight conditions are displayed as families of lines placed on the EMS scroll. During entry, the CM flight conditions of G (acceleration) and V (velocity) are displayed by means of a stylus which etches a vehicle G - V profile onto the scroll. This process allows a visual comparison of vehicle flight conditions in terms of G, V, and dG/dV (slope) and limiting flight conditions expressed in terms of these same parameters.

Figure 1 shows the two types of EMS scroll patterns used for lunar return entries. The first pattern, called the 3500 n mi limit pattern, contains a family of range limiting lines which display the conditions to prevent the CM from exceeding a maximum range of 3500 n mi. This family of lines defines conditions which allow the CM to exit the atmosphere in order to reach long downrange targets. Exit is defined by an acceleration load of less than G = 0.20. This pattern also contains a family of G on-set lines, which are the limits to prevent the CM from experiencing high levels of G, and a family of range guidelines to be discussed. The second scroll pattern, called the non-exit range limit pattern, contains a family of lines which display conditions that simultaneously prevent the CM from exceeding a range of 3500 n mi and exiting the atmosphere. This pattern also contains the same G on-set lines and the range guidelines as the 3500 n mi limit pattern.

If, during automatically controlled entries, the vehicle flight conditions meet the limiting flight conditions; and if the vehicle is not at the best recovery lift attitude, the PGNCS is assumed to have malfunctioned, and the crew should assume manual control of the entry and fly the EMS as a backup ranging device. The EMS provides the capability of backup ranging by displaying range guidelines which represent the potential range the CM could reach with a constant G flight mode.

The purpose of this document is (1) to explain and to verify the procedures used in the derivation of the EMS flight limit lines and range guidelines, and (2) to describe the verification of data relating to the flight limit lines and range guidelines.

# LIST OF SYMBOLS

| | |
|---|---|
| $dG/dV$ | Rate of change of acceleration load factor with respect to velocity, sec/ft |
| $G$ | Acceleration load factor, 32.17 ft/sec$^2$ |
| $h1$, $h2$, $h3$ | Altitudes of discontinuity of atmospheric density, ft |
| $V$ | Inertial velocity, ft/sec |

# DISCUSSION

NR (North American Rockwell Corporation) has derived sets of flight limiting lines displayed by the EMS to function as a monitor of PGNCS operation during entry. NR has also determined the range potential of the CM in such a manner that the EMS can provide the capability of backup ranging.

Sets of limiting flight conditions, which are represented by the flight limiting lines, and the range potential of the CM were derived on a four degree-of-freedom digital simulation program according to prescribed procedures. These procedures are described in the following four sections: (1) EMS G on-set lines, (2) EMS 3500 n mi range limit lines, (3) EMS skip limit lines, and (4) EMS range guidelines. It should be noted that the 3500 n mi limit scroll pattern contains lines (1), (2), and (4), while the non-exit scroll pattern contains lines (1), (3), and (4) (figure 1). At the present time, there will be four patterns on a lunar return EMS scroll. The patterns will alternate starting with the 3500 n mi limit pattern, then a non-exit pattern, etc.

## EMS G On-set Limit Lines

The purpose of the G on-set limit lines is to prevent the CM from experiencing entry acceleration loads in excess of 10 G's. The on-set lines accomplish their purpose by displaying flight conditions which, if experienced with the lift vector down, will always allow the pilot to avoid exceeding the 10 G level by rolling the CM to the best vehicle attitude, liftup. The flight conditions are called limiting flight conditions, since they set a limit on possible flight conditions beyond which the CM lift capability may be insufficient to prevent exceeding the 10 G level. The limiting flight conditions are displayed on the EMS scroll patterns in terms of the G, V, and dG/dV; i.e., it is the slope of the limit line at the particular G and V that is important.

The limit lines were generated according to the analytical model shown in figure 2. A standard atmosphere was utilized in the analytical model, since a preliminary analysis indicated that atmospheric density deviations caused only negligible effects on the final form of the G on-set limit lines.

In general, the procedure for determining the limiting flight conditions was to compute reverse trajectories from the design limit of 10 G's to the limiting flight conditions. In other words, the reverse trajectories were calculated so that their end conditions were the desired limiting flight conditions.

Flight conditions of altitude and flight path angle at 10 G's were determined for velocities between 36,100 fps and 18,000 fps. From these conditions, full liftup trajectories were computed in reverse to an exit condition of G = 0.0 (figure 3). These reverse trajectories were such that each point on them represented flight conditions of G, V, and dG/dV for which the design limit of 10 G's could not be exceeded if the lift vector were kept fully up.

To reach the limiting flight conditions with the lift vector down, as prescribed by the analytical model, flight conditions at various G-levels along each liftup, reverse trajectory were chosen as initial conditions for a series of reverse trajectories, each of which included a roll maneuver to a condition of full lift down. That is, beginning at a point on a full liftup trajectory, the calculation of a reverse trajectory and a roll maneuver to full lift down were initiated at the same time. Calculation of this trajectory continued for an additional two seconds after the lift vector down condition was reached. Figure 3 depicts the reverse trajectory from a full liftup trajectory, the associated rolling maneuver, and the additional two seconds of computation. The flight conditions of G, V, and dG/dV which occurred at the end of the two seconds were the desired EMS limiting flight conditions. It can be seen that the limiting conditions were derived according to the analytical model requirements of (a) protecting the 10 G design limit for EMS violations with the lift vector down, and (b) including a pilot response time of two seconds. Figure 3 illustrates, in terms of G and V, limiting flight conditions, or points, derived by the previously described procedure. The set of limiting points were connected to form a locus of points for each liftup, reverse trajectory discussed above.

NR plots of the loci of limiting points, expressed in terms of dG/dV and V, are given in figures 4 and 7 for the low and high L/D ratio, respectively. The dashed lines labeled h1, h2, and h3, were altitudes at which occurred the atmospheric break points of reference 2.

For the two L/D values, figures 5 and 8 show both the loci, in terms of G and V, and lines of constant dG/dV. To insure the proper placement of the constant dG/dV lines in these two figures, there was determined the velocity at which a particular dG/dV - locus intersection occurred in figures 4 or 7. In the appropriate figure 5 or 8, a point was marked on the line of constant dG/dV at the velocity determined from the intersection. The proper placement of the constant dG/dV lines was verified if the locus line used in figure 4 or 7 passed through the point marked in figure 5 or 8. For example, in figure 4 (L/D = 0.250), a value of dG/dV = -0.0010 occurs on locus line No. 1000 at a velocity of 28,180 fps. This dG/dV - locus intersection is marked as point No. 3. Considering then figure 5 (L/D = 0.250), a point also labeled as point No. 3 was marked on the line for dG/dV = -0.0010 at the velocity determined from the above mentioned intersection. Inspection of figure 5 shows that locus line No. 1000 does pass through point No. 3. Figures 4, 5, and 7, 8 show check point for several of the locus lines.

Figures 5 and 8 express the limiting flight conditions in terms of V, G, and dG/dV. It can be seen from these figures that the limiting conditions in terms of G and dG/dV, vary only slightly relative to a wide variation in velocity; i.e., G and dG/dV are nearly independent of velocity. It was for this reason that the velocity parameter was eliminated from consideration, allowing the limiting flight conditions to be expressed in terms of two parameters.

The elimination of velocity was accomplished by (a) selecting the minimum value of G for which a line of constant dG/dV occurred in figures 5 and 8, and (b) plotting dG/dV as a function of minimum G as shown in figures 6 and 9.

The reason for selecting the minimum value of G can be seen by considering that in order for an entering spacecraft to reach the design limit of 10 G's, it must pass through progressively increasing values of G. That is, smaller values of G occur at an earlier time in the entry than do larger values of G. Therefore, the minimum value of G was selected for each dG/dV since, over the entire velocity range, that value of G represented the earliest time in any entry at which the corresponding value of dG/dV could possibly occur. From this it can be seen that at any velocity other than the true minimum G velocity of figures 5 and 8, limiting flight conditions were made to occur at a slightly earlier time because they had been made to occur at a slightly earlier G-level. The earlier occurrence of limiting flight conditions meant that a recovery maneuver to the best vehicle attitude (liftup) could be initiated and completed at an earlier time, giving a maximum G which was always less than the design limit of 10 G's except, of course, at the minimum G velocity. The net effect, then, of the use of the minimum G was to give added protection to the design limit.

To verify that the correct values of dG/dV and minimum G had been selected, values of these parameters were determined in figures 5 and 8 and were compared to the plot in figures 6 and 9. For example, in figure 5, the value dG/dV = -0.0020 occurred at a minimum G level of 2.92, at the point C. In figure 6, the selected value of dG/dV did occur at the proper value of G.

The dashed lines in figures 5 and 6 were lines of discontinuity in the atmospheric density. Along these lines, the lines of constant dG/dV overlapped, giving two values of G for a single value of dG/dV. If the minimum G for a given dG/dV occurred at a point of atmospheric discontinuity, as in figure 5 for dG/dV = 0.0, that value of G was always taken as the minimum; i.e., no averaging of the two possible G values was done. This selection of minimum G resulted in the elimination of the atmospheric discontinuities as shown in figures 6 and 9.

At this point, the limiting flight conditions were expressed in terms of G and dG/dV for the two values of L/D (0.250 and 0.375). It was then necessary to combine the two sets of data in order to produce one set of limiting flight conditions applicable to the entire ranges of G, dG/dV and L/D. This was done by (a) selecting the minimum G value which occurred for all values of dG/dV in figures 6 and 9, and (b) plotting dG/dV as a function of minimum G in figure 10. The minimum value of G was selected at this point for the same reasons as described when the velocity variable was eliminated. An additional consideration here was that the minimum G represented the earliest time for the corresponding dG/dV not only over the entire velocity range but also over the entire range of L/D values.

The correctness of figure 10 was verified by overlaying figures 6 and 9 on a lamp table and then comparing G values for various values of dG/dV. From this it was seen that, for G levels less than G = 4.55, the G values for L/D = 0.250 were uniformly smaller than those values for L/D = 0.375. For G values greater than G = 4.55, the G values for L/D = 0.375 were the smaller values. Once this was known, the check was completed by overlaying figure 10 and each of figures 6 and 9 and by checking the appropriate portions of the dG/dV vs G lines for coincidence. In figure 10, the data are separated relative to L/D by a vertical line placed at G = 5.50. However, the comparison of figures 6 and 9 described above indicated that the separation of data should have been and actually was at G = 4.55.

The data expressed in figure 10 were transformed by integration to the continuous G on-set limit line required for the EMS display as shown in figure 11. The integration was expressed as follows:

$$dG = dG/dV \quad dV$$

and

$$G = G_o + \int dG_o/dV \quad dV$$

where $dG_o/dV$ corresponded to $G_o$ as defined in figure 10, and where the interval of integration was always 10 fps.

The resulting G on-set limit line was such that its slope was identical to the limiting dG/dV at every G and V. Since they were derived to be independent of velocity, the G on-set lines all had the same form and could have been placed at any desired position on the EMS scroll. This can be seen in figure 1 where the G on-set lines are placed every 2000 fps and are identically the same. They, of course, are also the same for both EMS patterns.

## EMS 3500 NM Range Limit Lines

These lines are associated with the exit scroll pattern and are intended to prevent the occurrence of trajectory conditions which result in entry ranges larger than the specified maximum 3500 n mi. The entry range is taken to be the ground range from entry interface (altitude of 400,000 ft) to drogue chute deployment. The range limit lines accomplish their purpose by displaying flight conditions which, if experienced with the lift vector up, will always allow the pilot to avoid exceeding the range limit by rolling the CM to lift down. As was the case with the G on-set lines, the flight conditions discussed here are called limiting flight conditions since they set a limit on possible flight conditions beyond which the predicted CM lift capability would be insufficient to prevent exceeding the range limit. The limiting flight conditions are displayed by the EMS in terms of the G, V, and dG/dV.

The analytical model which was used to develop the range limit lines is shown in figure 12. The $\pm 3\sigma$ values of L/D were combined with the respective atmospheric density deviations, resulting in two analytical models. The other two combinations of L/D and atmosphere were considered in a manner to be discussed.

The general procedure for determining the range limiting flight conditions was to compute reverse trajectories from known flight conditions to the range limiting conditions. The reverse trajectories were calculated so that their end conditions were the desired range limiting conditions.

The design limit of a specified range was not in itself enough to determine initial flight conditions for the reverse trajectories. The initial conditions were determined in two steps. First, a trajectory called the critical trajectory was obtained, and second, flight conditions for a series of atmospheric "skip" maneuvers were determined.

The critical trajectories for the two values of L/D are shown in figures 13 and 17. These trajectories were characterized by an entry velocity of 36,100 fps and by a constant roll angle, or lift vector orientation, which was maintained until the acceleration was G = 0.2 with dG/dV = 0.0. At this point, the lift vector was rolled to 90°, a condition of zero lift, and was maintained there until an altitude of 25,000 ft was reached (drogue chute deployment). The two trajectories selected gave the maximum velocities at which the minimum acceleration G = 0.20 could occur consistent with the range limit; neither trajectory exceeded a range of 3500 n mi. In summary, the critical trajectories were found by varying the entry flight path angle and the roll angle until the G = 0.20 occurred with dG/dV = 0 at a maximum velocity while not exceeding the range limit.

The constant roll angle for the high L/D critical trajectory was 127.5°, and its total range was 3500 n mi. For the combination of low atmosphere and low L/D, it was found that to reach exactly the 3500 n mi range, a roll angle in excess of 85 percent negative lift was required. (The roll angle corresponding to 85 percent negative lift is $\phi$ = arc cos (.85) = 148.216°.) Since the remaining 15 percent of negative lift had been established by ground rule as a safety factor with respect to supercircular exit avoidance, the critical trajectory for this L/D and atmosphere combination was developed with a constant roll angle of 148.216°. From references 3 and 4, the coefficients of drag for the low and high L/D values were 1.353 and 1.188, respectively. The larger drag of the low L/D critical trajectory caused this trajectory to realize a range of only 3410 n mi, instead of the allowable 3500 n mi range.

For these critical trajectories, and for a group of trajectories to be discussed, the roll angle was set to 90° at G = 0.20 and was held at that value until drogue deployment because, in meeting the range requirement, this allowed the occurrence of exit velocities which were in the same range as exit velocities obtained in entries controlled by the primary guidance system. The result of this was that the final form of the range limit lines was less constraining to the up-phase portion of automatically controlled entries.

As mentioned before, the critical trajectories were characterized by the fact that they yielded the maximum velocity for which a minimum G = 0.20 could be obtained, consistent with the range limit. The range limit lines for the exit pattern do allow exits to occur (exit means G levels less than G = 0.20), and it was necessary to determine the minimum exit velocity for which the range limit could be approached. This was accomplished by varying the entry flight path angle of full positive lift trajectories until a range of 3500 n mi was obtained. The two resulting trajectories were called maximum trajectories because of the rather high G-loads which were encountered. Figure 18 shows the maximum trajectory for the high L/D. No maximum trajectory figure was available for the low L/D.

The critical and maximum trajectories established upper and lower velocity bounds at G = 0.20 for which the range limit could be approached but not exceeded. It was then necessary to determine flight conditions at G = 0.20 (with dG/dV not zero) and between the velocity bounds for which the range limit could be met. These exit conditions were determined according to the procedures of reference 1. Briefly, these procedures required the calculation of trajectories whose flight mode was a constant G during the super-circular flight region to a velocity where full positive lift was implemented and maintained to exit, G = 0.20. Subsequent to exit, a zero lift attitude was maintained to drogue chute deployment. These trajectories were chosen so that they approached the range limit, and their exit flight conditions were the desired ones between the two velocity bounds.

The critical trajectory was combined with the exit flight conditions just described to form the set of initial conditions for the reverse trajectories. One group of reverse trajectories was flown with the lift vector

full down. At various G-levels on each of these reverse trajectories, there was computed another set of reverse trajectories which included a roll maneuver to full lift up. After the full liftup attitude was reached, calculation continued an additional two seconds to simulate the pilot response time of the analytical model. The flight conditions of G, V, and dG/dV which resulted at the end of the two-second response period were the desired range limiting flight conditions. For each of the reverse full lift down trajectories, there was formed a locus of flight conditions. All of these limiting conditions occurred at G-levels greater than the levels for the critical trajectory.

To determine limiting flight conditions for G-levels less than the critical trajectory, a series of reverse trajectories were again computed. However, these reverse trajectories were all initialized at the velocity for which the critical trajectory reached G = 0.20, and they all incorporated constant roll angles less than that of the critical trajectories. At various G-levels on each of these reverse trajectories, there were initialized reverse trajectories which included a rolling maneuver to the full liftup condition and which included the two-second pilot response time. Again, loci of limiting flight conditions were obtained.

Figures 14 and 19 show the loci of range limiting flight conditions expressed in terms of G and V. Figures 15 and 20 show the loci in terms of dG/dV and V. Lines of constant G for the loci are plotted in figures 16 and 21. The placement of the lines of constant G was checked according to the following procedures. The velocity at which occurred G-locus intersections was determined in figures 14 and 19. These same points of intersection were plotted in figures 15 and 20 according to velocity. The points then represented different values of G for the locus lines, and it was then necessary to transfer the points to figures 16 and 21, where several check points are shown.

In figure 16, for the low L/D and least dense atmosphere, it was found that the check points did not fall exactly on the corresponding lines of constant G. For the lower levels of G, it was found that a "smoothing" of the lines between the check points had been used to effect a greater degree of uniformity between the different lines. In all cases, the difference between the check point and the indicated G line was quite small so that no compromise was made with the purpose of the skip limit lines. This was further verified in digital entry simulations performed by NR. This "smoothing" technique was also utilized in some of the higher levels of G; for example, in G = 6. For the lines G = 9 and G = 10, it was found that some of the data of figures 14 and 15 had been extrapolated from lower levels of G. The extrapolation resulted from the fact that there were only a few data points at the higher G's due to the impossibility of occurrence for some of the flight conditions. For example, at G = 10, flight condition data was obtained mainly for velocities between 31,000 - 35,000 fps, since it was physically impossible for any flight conditions to occur at most other velocities. The flight conditions at these other velocities were obtained by extrapolation combined with whatever true

data points were available. Engineering judgment played a role in this, primarily in the extrapolation process. It should be noted that on an actual EMS scroll pattern, the skip limit lines are not calculated for levels higher than G = 9, so that most of the regions where engineering judgment and extrapolation were used can present no problem.

In figure 21, for the high L/D and most dense atmosphere, the check points agreed very well with the lines of constant G. Some "smoothing" was done in the original construction of the lines. For this combination of L/D and atmosphere, sufficient data were accumulated for flight conditions over the entry velocity range so that extrapolation was unnecessary.

The range limiting conditions which had been generated at this point considered two analytical models whose differences were the L/D value and atmosphere used. Actually, four combinations of L/D and atmosphere were possible, but the work involved in obtaining limiting conditions for these four combinations was prohibitive. It was decided by NR to use the two combinations already noted and then to check the validity of the resulting limiting flight conditions with respect to the other two combinations. The verification of the limiting flight conditions was accomplished through digital simulation.

Verification runs were initialized at a variety of limiting flight conditions with the vehicle in the worst attitude, lift up. Forward calculation was begun and continued for two seconds, at which time the vehicle was rolled to the best attitude, lift down. If the range of the ensuing trajectory violated the design limit, the limiting flight conditions were altered until protection of the design limit was ensured. This was not a point-by-point alteration, but rather the alterations were required over certain velocity and G regions.

In this manner, a set of range limiting flight conditions were obtained which were applicable to the entire range of L/D values and atmospheric density deviations. The final set of flight conditions is shown in figure 22. Table I is a tabulation of the data from this figure; a matrix form was required for computer processing. The data outside the heavy boundary were extrapolated to obtain a completed matrix required for use by a table lookup routine in the computer. The extrapolated data were never used in generating the EMS range limit lines.

The data in Table I were integrated in a manner similar to that used for the G on-set lines. Since the range limit lines were not derived to be independent of velocity, the lines were not all identical in shape. Adjustments in the lines for EMS velocity errors were included during the computer processing according to the methods described in reference 1. The final version of 3500 n mi limit lines can be seen in figure 1.

## EMS Skip Limit Lines

These lines are associated with the non-exit scroll pattern and are intended to prevent the occurrence of trajectory conditions which would result in either exiting the atmosphere or the entry range being larger than 3500 n mi. A skip is said to occur if the CM experiences an acceleration loading of less than G = 0.20 after the initial pass into the atmosphere.

The skip limit lines accomplish their purpose by displaying to a pilot flight conditions which, if they are experienced with the lift vector up, will always allow the pilot to avoid exceeding either design limit by rolling the CM to the best vehicle attitude, lift down. The flight conditions to be discussed are called limiting flight conditions, since they represent a limit on possible flight conditions beyond which an assumed CM lift capability is insufficient to prevent the exceeding of the two design limits. The limiting flight conditions are displayed by the EMS in terms of the G, V, and dG/dV.

The analytical model employed in the development of the skip limit lines is shown in figure 23. This model differs from the 3500 n mi limit line model only in the addition of the minimum G as a design limit. The $\pm 3\sigma$ values of L/D were combined with the respective atmospheric density deviations, resulting in two analytical models. The other two combinations of L/D and atmosphere were incorporated in a manner to be discussed.

The general NR procedure for determining the skip limiting flight conditions was to compute reverse trajectories from known flight conditions to the skip limiting flight conditions. The reverse trajectories were calculated so that their end conditions were the desired skip limiting flight conditions.

The minimum G design limit was sufficient to define a partial set of initial flight conditions for a series of reverse trajectories. That is, flight conditions of altitude and flight path angle were determined at G = 0.20 and dG/dV = 0.0 over a range of velocities.

A second set of initial flight conditions for reverse trajectories was obtained by using the two critical trajectories discussed under the 3500 n mi range limit lines. These trajectories were derived so as to satisfy the range limit, but they also furnished the maximum velocity for which a constant acceleration of G = 0.20 could be obtained. The critical trajectories, therefore, did not exceed the design limits of the skip limit lines, and they did set an upper velocity bound for which the first set of initial flight conditions discussed above was determined.

The lower velocity bound for the first set of initial flight conditions was established by varying the entry flight path angles of full liftup trajectories (entry velocity = 36,100 fps) until G = 0.20 was no longer

attainable. The smallest velocity for which G = 0.20 was achieved was the desired lower velocity bound. This smallest velocity was found to be 20,000 fps for both analytical models.

With the establishment of a complete set of initial flight conditions, a series of reverse full lift down trajectories was computed. At various levels of G on each of these lift down trajectories, there was computed another set of reverse trajectories which included a roll maneuver to full lift up. After the full liftup attitude was reached, calculation continued an additional two seconds to simulate the pilot response time. The flight conditions of G, V, and dG/dV which resulted at the end of the two second response period were the desired skip limiting flight conditions. For each of the reverse full lift down trajectories, there was formed a locus of skip limiting flight conditions.

The loci of flight conditions for those reverse trajectories initialized at the level G = 0.20 are shown in figures 24(a) and 27(a). Each figure expresses the loci in terms of h vs V and in terms dG/dV vs V. Lines of constant G are shown on each plot. Figures 25(a) and 28(a) show all loci in terms of G and V, and lines of constant dG/dV are shown in each of these plots.

In figures 24(a) and 27(a) the locus-G intersect points of the two graphs were checked with respect to velocity. That is, the velocity at which occurred a locus-G intersect point in the h vs V plot should have been the same as the velocity of the intersection in the dG/dV vs V plot. Since the two plots in each figure shared a common velocity axis, the check was performed by examining corresponding locus-G intersect points to see that they both occurred on the same velocity line. This check was performed visually, and no check points were plotted.

The placement of the loci of limiting flight conditions in figures 25(a) and 28(a) was checked in two ways. First, in figures 24(a) and 27(a), the velocity at which occurred locus-dG/dV intersection was determined. Then, in figures 25(a) and 28(a), corresponding points were marked on lines of constant dG/dV at the above velocities. For example, in figure 24(a) the intersection of dG/dV = 0.00225 and locus line No. 2 occurs at a velocity of 24,550 fps. In figure 25(a) a point was marked on the example dG/dV line at the determined velocity, and it can be seen that locus line No. 2 does pass through this check point. Several check points are shown in the figures.

The second method of checking the placement of the locus lines was to compare locus-G intersections in figures 24(b) and 27(b) to the same intersections in figures 25(b) and 28(b). The comparison was made by utilizing velocity to transfer intersect points of the first two figures to the second set of figures.

In figures 25(a) and 28(a), the locus lines whose numbers have primes associated with them are those locus lines which were obtained in the development of the range limit lines. Since the placement of those lines had been checked previously, no check points are shown for them in these figures.

Most check points showed that placement of the locus lines and lines of constant dG/dV was consistent with the data of figures 24(a) and 27(a). Some deviation in placement was indicated, but this was a result of a slight shifting of the locus lines and the lines of constant dG/dV. This shifting was done to provide more uniformity between lines but was done so that no compromise was made with the purpose of the skip limit lines. For example, some of the dG/dV lines were shifted slightly in the direction of increasing velocity. The result of this was that, for a given level of G, a value of dG/dV was made to occur at a slightly higher velocity, or at a slightly earlier time. The earlier time carried over to the final form of the skip limit line so that if the CM experienced a limiting flight condition, as displayed by the EMS, a recovery maneuver would be initiated at a slightly earlier time than it would have been if the limit data had not been shifted. The earlier time of recovery gave added protection to the design limits.

Figures 26 and 29 show lines of constant G in terms of dG/dV and V. The placement of the G lines was checked by transferring G-dG/dV intersect points of figures 25(c) and 28(c) to figures 26 and 29. The transfer was done according to velocity. The check points showed good placement of the lines but indicated that some smoothing of the constant G lines was done in their construction. Deviations were very small in all instances, and digital simulations have indicated that the deviations did not degrade the protection of the design limits.

The limiting flight conditions above were tested to insure their validity over combinations of high and low values of L/D with low and high atmospheric density deviations. Verification of the skip limit conditions was accomplished through digital simulations in which a CM was initialized with the lift vector up at various limiting flight conditions. If a recovery maneuver did not prevent exceeding the design limits, the initial flight conditions were altered until a recovery maneuver was successful in protecting the design limits.

There was finally obtained a set of skip limiting flight conditions which were applicable to the entire range of L/D values and atmospheric density deviations. This set is shown in figure 30.

Table II is a tabulation of the data of figure 30. The data were integrated, in a manner similar to that used for the G on-set lines, to form the EMS skip limit lines shown in figure 31. In Table II, the data outside the heavy boundary were extrapolated to obtain a completed matrix required for use by the computer. The extrapolated data were never used in generating the EMS skip limit lines. Adjustments in the lines for EMS velocity errors were accounted for during the computer processing according to the methods of reference 1. The final version of the EMS skip limit lines can be seen in figure 1.

## EMS Range Guidelines

The EMS range guidelines provide during entry the capability of ranging to a known landing target. The guidelines, which represent potential range, are interpreted in conjunction with the spacecraft G-V flight trace in the following manner: when the flight trace intersects a range guideline, the range indicated on the guideline is the potential range the spacecraft could travel, if the G level at the intersect point were maintained as constant as possible for the remainder of the entry.

The analytical model under which the range guidelines were developed is shown in figure 32. An average value of L/D was used with a nominal atmosphere, since off-nominal L/D and atmospheric condition can be compensated for by the flight mode. Since entry azimuths are mission dependent, the single entry azimuth of $90^{\circ}$ was used in the development of the range guidelines.

Range guidelines were developed using true inertial velocity and the velocity calculated by the EMS. Guidelines developed from the true inertial velocity were chosen for the EMS display, since the use of the EMS velocity introduced what were essentially unpredictable errors in the scroll placement of the guidelines.

The guidelines were developed by flying entries with a constant G flight mode. From these entries, it was possible to obtain great circle range in terms of G and V as required for EMS display. Figures 33(a) and 33(b) show range and velocity for various values of constant G. Figures 34(a) and 34(b) show G and V for lines of constant range. These last two figures show the range guidelines in the EMS format. The guidelines extend to a line called the subcircular glide trajectory which represents essentially a full liftup trajectory from an earth orbital entry. For levels of G less than or equal to those of the glide trajectory, it is impossible to maintain a flight mode of constant G, and the range lines are meaningless for those levels of G.

The placement of the constant range lines in figures 34(a) and 34(b) was checked with respect to the data of figures 33(a) and 33(b). The check consisted of determining the velocity of Range - G intersect points in figures 33(a) and 33(b). In figures 34(a) and 34(b), check points were plotted for the various G - V combinations determined in the previous figures. Placement of the range guidelines was verified, if the correct guideline passed through the check point. Check points are shown in the figures. The final version of the EMS range guidelines can be seen in figure 1.

## DISCUSSION OF RESULTS

The discussion of results is divided into the same four sections as the discussion: (1) EMS G on-set limit lines, (2) EMS 3500 n mi range limit lines, (3) EMS skip limit lines, and (4) EMS range guidelines.

### EMS G On-set Limit Lines

Reference 2 presents the NR derivation of the G on-set limit lines. An examination of this reference shows that the on-set limit lines were derived according to the procedures of reference 1. The data of reference 2 are contained in figures 4 - 11 and were checked for consistency between the figures; no inconsistencies were found. The placement of lines of constant dG/dV in figures 5 and 8 showed very good agreement with the data of figures 4 and 7. The selection of minimum G for values of dG/dV, as shown in figures 6 and 9, was verified by a comparison with the data of figures 5 and 8. Through a selection of minimum G, the data of figures 6 and 9 were combined to yeild figure 10. The data of this figure were separated relative to L/D by a vertical line placed at G = 5.50, and during the checking procedure, it was found that the separation line should have been placed at G = 4.55. The incorrect placement of the line was attributed to a graphical error which occurred during the drawing of the plot. This error in no way affected the correctness of the data in the figure.

### EMS 3500 NM Range Limit Lines

References 3 and 4 present the NR derivation of the range limit lines for the low and high values of L/D, respectively; the procedures outlined in these two references conform to reference 1. The data of references 3 and 4 are shown in figures 13 - 29, and these data were checked for consistency whenever possible. Some apparent inconsistencies appeared in the check of the constant G lines in figure 16, but these were explained by either a smoothing of the constant G lines to give greater uniformity between lines or by a necessary extrapolation of the constant G caused by a scarcity of flight condition data at higher G levels.

### EMS Skip Limit Lines

The derivation of the skip limit lines is contained in reference 6, and the derivation procedures conform to the procedural requirements of reference 1. The limiting flight condition data of reference 6, which are shown in figures 24 - 30, were checked to insure that the presented data were consistent between the figures.

In figures 25(a) and 28(a), a series of checks indicated that the placement of lines of constant dG/dV did not agree exactly with the data of figures 24 (a) and 27(a). It was found that NR had slightly adjusted the dG/dV lines to yield more uniformity between different lines. All adjustments were made so that, for all entries, adjusted values of dG/dV occurred slightly earlier in time, giving added protection to the design limits.

In figures 26 and 29, check points indicated that lines of constant G were not placed in exact agreement with the data of figures 25(c) and 28(c). It was found that the lines of constant G had been "smoothed" slightly to facilitate integration of the limit data which yielded the EMS skip limit lines. Digital simulations performed by NR showed that the adjustments to the lines of constant G in no way degraded the protection of the design limits.

## EMS Range Guidelines

Reference 7 presents the NR derivation of the range guidelines. The data of this reference are contained in figures 31 - 33. In figure 33(b), a check of the data indicated an error in the placement of the 75 n mi range guideline with respect to the data of figure 32(b). NR agreed that an error had been made and estimated the error to be between two and four nautical miles for levels of G between G = 2.5 and G = 3.0, and between G = 7.0 and G = 8.0. These were the levels of G for which the error occurred.

Check points indicated that the 50 n mi range guideline was placed correctly so that the small error in the 75 n mi range guideline would be accounted for during manual ranging as the 50 n mi guideline was approached. It was concluded, therefore, that the error present in the 75 n mi range guideline did not compromise either crew safety or the ability of the EMS to provide adequate ranging information. It should also be noted that in the region of the scroll pattern, the range scaling is approximately .03 in. per mile so that the error is within the expected control performance, and the range guideline is still useful.

# CONCLUSIONS

The following conclusions are based upon the results of the EMS flight limit line and range guideline verification study:

a. The EMS G on-set limit lines, the EMS 3500 n mi range limit lines, and the EMS skip limit lines were correctly developed. Therefore, the scroll patterns investigated can be used to monitor PGNCS performance during all Apollo entries.

b. The EMS range guidelines, with one exception, were correctly developed. The one exception can be accounted for during manual ranging so that, in the event of a PGNCS malfunction during entry, the range guidelines can be used in backup ranging.

REFERENCES

1. NR document SD 68-146: Entry Monitor System (EMS) Flight Pattern Limit Line Generation and Development Procedures. February 1968.

2. NR IL FT/EP-68-018: EMS Critical On-Set Limits. February 16, 1968.

3. NR IL FT/EP-68-071: EMS 3500 NM Range Limits for a 0.25 L/D and Least Dense Atmosphere. June 12, 1968.

4. NR IL FT/EP-68-072: EMS 3500 NM Range Limits for an 0.375 L/D and Most Dense Atmosphere. July 16, 1968.

5. NR IL FT/EP-68-073: EMS Composite 3500 NM Range Limits for the Lunar Scroll Configuration. July 12, 1968.

6. NR IL FT/EP-68-080: EMS Non-Exit Off-Set Limits. July 12, 1968.

7. NR IL FT/EP-68-084: EMS Lunar Configuration Range Guidelines. July 8, 1968.

TABLE I. - FINAL SET OF DATA FOR RANGE LIMITING FLIGHT CONDITIONS

COMPOSITE DATA MATRIX $0.250 \le L/D \le 0.375$

Inertial Velocity FPS

| dG/dV | G=0.05 | G=0.25 | G=0.50 | G=0.75 | G=1.00 | G=1.50 | G=2.00 | G=3.00 | G=4.00 | G=5.00 | G=6.00 | G=7.00 | G=8.00 | G=9.00 | G=10.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| +0.0036 | 21,485 | 21,900 | 22,200 | 22,570 | 22,730 | 22,855 | 23,010 | 23,555 | 24,165 | 24,725 | 25,100 | 25,355 | 25,610 | 25,865 | 26,290 |
| +0.0032 | 21,995 | 22,395 | 22,710 | 23,045 | 23,215 | 23,345 | 23,500 | 24,020 | 24,590 | 25,115 | 25,470 | 25,745 | 26,025 | 26,380 | 26,885 |
| +0.0028 | 22,485 | 22,855 | 23,180 | 23,495 | 23,655 | 23,805 | 24,000 | 24,500 | 25,055 | 25,550 | 25,900 | 26,200 | 26,555 | 27,105 | 27,625 |
| +0.0024 | 22,945 | 23,300 | 23,635 | 23,905 | 24,100 | 24,305 | 24,525 | 25,050 | 25,600 | 26,050 | 26,410 | 26,815 | 27,380 | 27,955 | 28,425 |
| +0.0020 | 23,360 | 23,710 | 24,040 | 24,260 | 24,455 | 24,735 | 25,000 | 25,600 | 26,225 | 26,685 | 27,155 | 27,700 | 28,370 | 28,950 | 29,610 |
| +0.0016 | 23,750 | 24,095 | 24,400 | 24,600 | 24,755 | 25,100 | 25,455 | 26,300 | 27,000 | 27,800 | 28,490 | 29,250 | 29,925 | 30,600 | 31,660 |
| +0.0012 | 24,105 | 24,425 | 24,700 | 24,905 | 25,100 | 25,[illegible]80 | 26,160 | 27,400 | 28,500 | 29,500 | 30,450 | 31,275 | 32,200 | 32,925 | 33,575 |
| +0.0008 | 24,430 | 24,715 | 25,005 | 25,400 | 25,910 | 26,930 | 27,800 | 29,200 | 30,400 | 31,700 | 32,650 | 33,650 | 34,450 | 35,150 | 35,800 |
| +0.0004 | 24,750 | 25,030 | 25,880 | 26,785 | 27,630 | 28,750 | 29,710 | 31,200 | 32,700 | 34,000 | 35,075 | 36,000 | 37,000 | 37,650 | 38,500 |
| 0 | 25,210 | 26,500 | 27,500 | 28,500 | 29,200 | 30,500 | 31,550 | 33,450 | 35,000 | 36,500 | 37,700 | 38,700 | 39,700 | 40,500 | 41,400 |
| -0.0004 | 26,000 | 27,285 | 29,000 | 30,175 | 31,000 | 32,200 | 33,625 | 35,800 | 37,790 | 39,500 | 40,900 | 42,250 | 43,450 | 44,500 | 45,450 |
| -0.0008 | 26,950 | 28,775 | 30,475 | 31,500 | 32,620 | 34,400 | 36,000 | 38,850 | 41,100 | 43,050 | 44,550 | 46,000 | 47,200 | 48,350 | 49,350 |
| -0.0012 | 27,960 | 29,860 | 31,775 | 33,050 | 34,450 | 36,750 | 38,800 | 42,000 | 44,550 | 46,600 | 48,500 | 49,950 | 51,150 | 52,400 | 53,400 |
| -0.0016 | 29,000 | 30,900 | 33,225 | 34,900 | 36,575 | 39,400 | 41,450 | 44,800 | 47,450 | 49,550 | 51,450 | 52,850 | 54,100 | 55,400 | 56,450 |
| -0.0020 | 29,925 | 32,000 | 34,850 | 37,000 | 39,000 | 42,000 | 44,350 | 47,600 | 50,600 | 52,500 | 54,000 | 55,500 | 56,700 | 57,700 | 59,000 |
| -0.0024 | 30,750 | 33,220 | 36,725 | 39,400 | 41,200 | 44,050 | 46,450 | 50,200 | 53,300 | 55,600 | 57,550 | 59,100 | 60,500 | 61,950 | 63,450 |
| -0.0028 | 31,570 | 34,450 | 37,700 | 40,600 | 42,700 | 46,500 | 49,350 | 53,400 | 56,350 | 58,750 | 60,800 | 62,600 | 64,450 | 66,250 | 68,150 |
| -0.0032 | 32,250 | 35,375 | 39,000 | 41,900 | 44,500 | 48,500 | 51,550 | 56,100 | 59,450 | 62,100 | 64,500 | 66,500 | 68,550 | 70,900 | 73,400 |
| -0.0036 | 33,575 | 36,950 | 40,500 | 43,700 | 46,450 | 50,950 | 54,400 | 58,850 | 62,450 | 65,300 | 67,800 | 70,200 | 72,850 | 75,650 | 79,000 |
| -0.0046 | 36,780 | 42,500 | 46,750 | 50,150 | 52,550 | 56,400 | 59,350 | 63,950 | 67,600 | 70,750 | 73,750 | 76,750 | 79,700 | 82,850 | 86,400 |

TABLE II. - FINAL SET OF DATA FOR SKIP LIMITING FLIGHT CONDITIONS ($0.250 \leq L/D \leq 0.375$)

| dG/dV | INERTIAL VELOCITY ~FPS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | G=0.05 | G=0.25 | G=0.50 | G=0.75 | G=1.00 | G=1.50 | G=2.00 | G=3.00 | G=4.00 | G=5.00 | G=6.00 | G=7.00 | G=8.00 | G=9.00 | G=10.00 |
| +0.00250 | 250 | 1750 | 3750 | 5500 | 7000 | 8500 | 10,250 | 14,000 | 16,750 | 18,500 | 20,500 | 22,500 | 23,700 | 24,540 | 25,650 |
| +0.00225 | 750 | 2500 | 4750 | 6900 | 8500 | 10,500 | 12,750 | 16,250 | 19,000 | 21,750 | 23,750 | 24,250 | 25,000 | 26,250 | 27,200 |
| +0.00200 | 1750 | 4000 | 6500 | 9000 | 11,000 | 13,000 | 15,000 | 19,000 | 21,750 | 23,750 | 24,900 | 25,825 | 26,700 | [illegible] | 28,675 |
| +0.00175 | 2750 | 5500 | 8500 | 11,200 | 12,250 | 16,000 | 18,000 | 22,000 | 24,100 | 25,450 | 26,650 | 27,625 | 28,625 | 29,450 | 30,350 |
| +0.00150 | 4000 | 7500 | 11,250 | 14,000 | 16,500 | 19,000 | 21,500 | 24,350 | 25,950 | 27,125 | 28,350 | 29,425 | 30,450 | 31,175 | 31,950 |
| +0.00125 | 6000 | 10,250 | 14,500 | 17,500 | 20,000 | 22,500 | 23,725 | 26,100 | 27,550 | 28,750 | 30,000 | 31,000 | 31,850 | 32,625 | 33,300 |
| +0.00100 | 8500 | 13,500 | 18,250 | 21,500 | 23,250 | 24,800 | 25,800 | 27,600 | 29,150 | 30,500 | 31,450 | 32,500 | 33,300 | 34,000 | 34,675 |
| +0.00075 | 12,200 | 17,000 | 21,200 | 24,200 | 25,300 | 26,400 | 27,450 | 29,100 | 30,650 | 32,000 | 32,950 | 33,900 | 34,725 | 35,450 | 36,050 |
| +0.00050 | 16,500 | 20,550 | 24,675 | 26,200 | 26,850 | 27,840 | 28,875 | 30,600 | 32,150 | 33,425 | 34,450 | 35,400 | 36,250 | 36,950 | 37,775 |
| +0.00025 | 21,300 | 24,000 | 26,450 | 27,500 | 28,100 | 29,300 | 30,225 | 32,100 | 33,550 | 34,850 | 36,000 | 37,000 | 37,900 | 38,700 | 39,500 |
| 0 | 23,800 | 25,825 | 27,600 | 28,700 | 29,300 | 30,400 | 31,550 | 33,450 | 35,000 | 36,500 | 37,900 | 38,700 | 39,700 | 40,500 | 41,400 |
| -0.00025 | 25,250 | 27,100 | 28,575 | 29,600 | 30,400 | 31,500 | 32,875 | 34,850 | 36,800 | 38,100 | 39,300 | 40,500 | 41,500 | 42,400 | 43,300 |
| -0.00050 | 26,250 | 28,000 | 29,475 | 30,500 | 31,400 | 32,700 | 34,175 | 36,575 | 38,500 | 40,000 | 41,200 | 42,400 | 43,500 | 44,300 | 45,400 |
| -0.00075 | 27,000 | 28,725 | 30,300 | 31,350 | 32,400 | 34,100 | 35,700 | 38,100 | 40,300 | 41,800 | 43,100 | 44,400 | 45,600 | 46,400 | 47,500 |
| -0.00100 | 27,700 | 29,350 | 31,125 | 32,250 | 33,475 | 35,600 | 37,550 | 39,900 | 42,250 | 43,800 | 45,100 | 46,500 | 47,700 | 48,500 | 49,700 |
| -0.00125 | 28,300 | 30,000 | 31,900 | 33,250 | 34,700 | 37,000 | 39,000 | 41,700 | 44,250 | 46,000 | 47,300 | 48,700 | 49,900 | 50,750 | 52,000 |
| -0.00150 | 28,875 | 30,625 | 32,825 | 34,400 | 36,000 | 38,700 | 40,700 | 43,500 | 46,350 | 48,000 | 49,500 | 50,900 | 52,100 | 53,050 | 54,250 |
| -0.00175 | 29,400 | 31,300 | 33,800 | 35,700 | 37,375 | 40,250 | 42,500 | 45,500 | 48,500 | 50,200 | 51,700 | 53,000 | 54,400 | 55,250 | 56,600 |
| -0.00200 | 29,725 | 32,000 | 34,850 | 37,000 | 39,000 | 42,000 | 44,350 | 47,600 | 50,600 | 52,500 | 54,000 | 55,500 | 56,700 | 57,700 | 59,000 |
| -0.00225 | 30,450 | 32,750 | 36,000 | 38,400 | 40,500 | 43,750 | 46,300 | 49,600 | 52,750 | 54,800 | 56,300 | 57,750 | 59,000 | 60,000 | 61,500 |
| -0.00250 | 30,950 | 33,520 | 37,200 | 39,800 | 42,000 | 45,600 | 48,300 | 51,800 | 55,000 | 57,100 | 58,600 | 60,100 | 61,500 | 62,500 | 63,800 |
| -0.00525 | 39,350 | 44,400 | 52,200 | 58,700 | 62,600 | 67,500 | 72,100 | 77,000 | 81,700 | 84,400 | 86,700 | 88,400 | 89,500 | 91,000 | 92,700 |

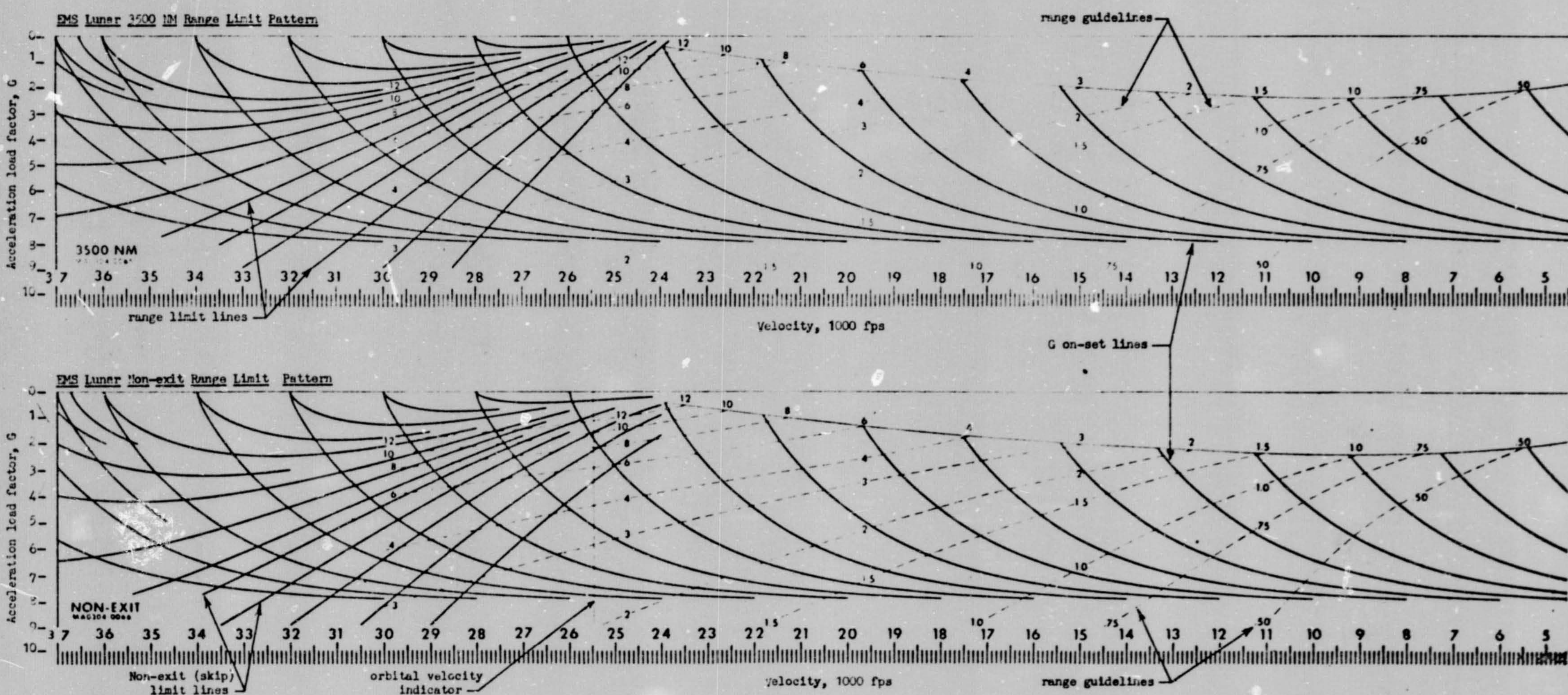


Figure 1. - EMS scroll patterns for lunar return entries

DESIGN LIMIT: 10 G MAXIMUM

DESIGN LIMIT PROTECTED FOR VIOLATION WITH FULL LIFT DOWN

PILOT RESPONSE TIME = 2 SEC

TIME FROM LIFT DOWN TO LIFT UP = 14.5 SEC

VEHICLE WEIGHT = 13,500 LBS

NOMINAL 1962 U. S. STANDARD ATMOSPHERE

$$L/D = \begin{cases} 0.375 \\ 0.250 \end{cases}$$

Figure 2. - Analytical model for G on-set lines

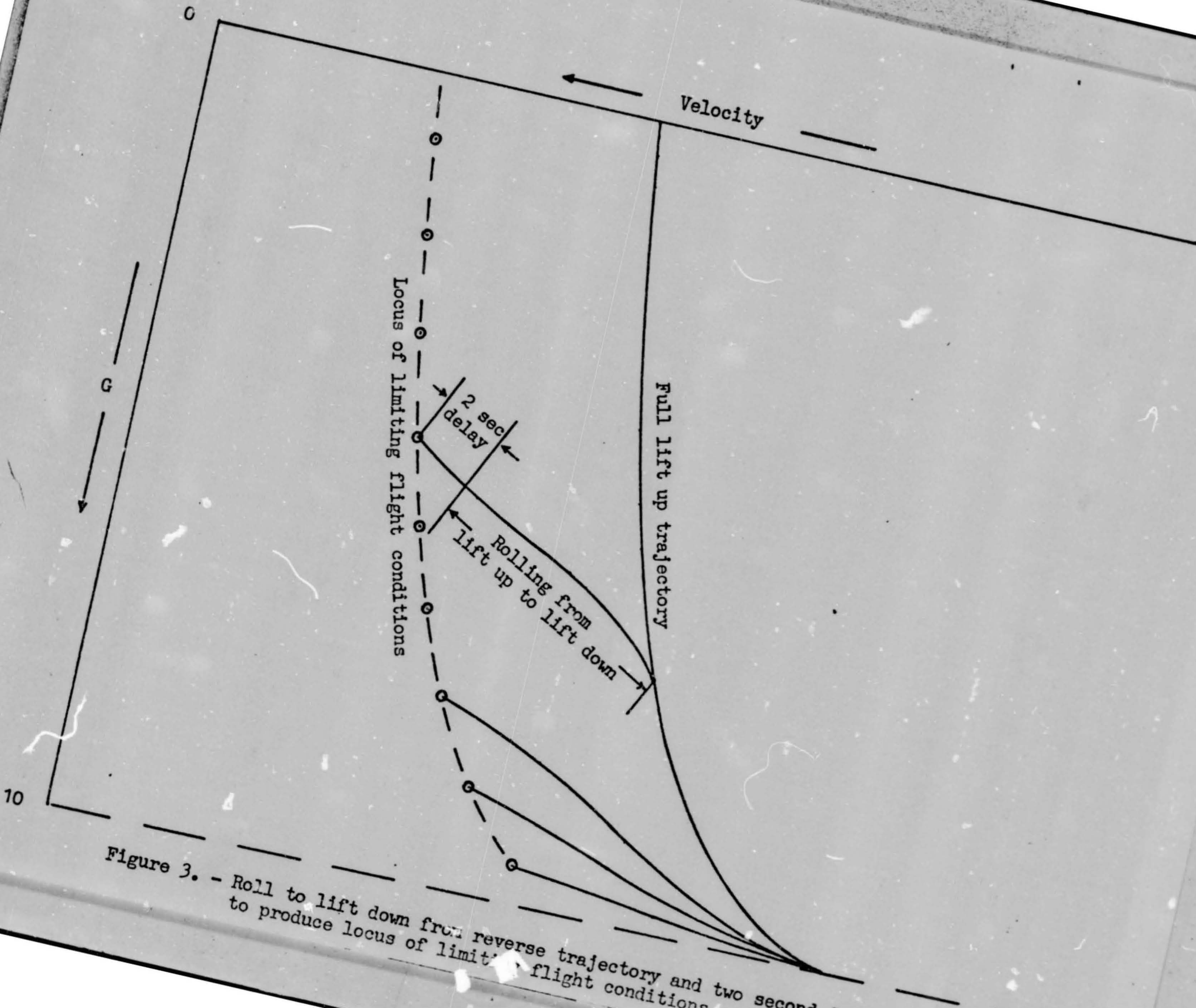


Figure 3. - Roll to lift down from reverse trajectory and two second delay to produce locus of limiting flight conditions.

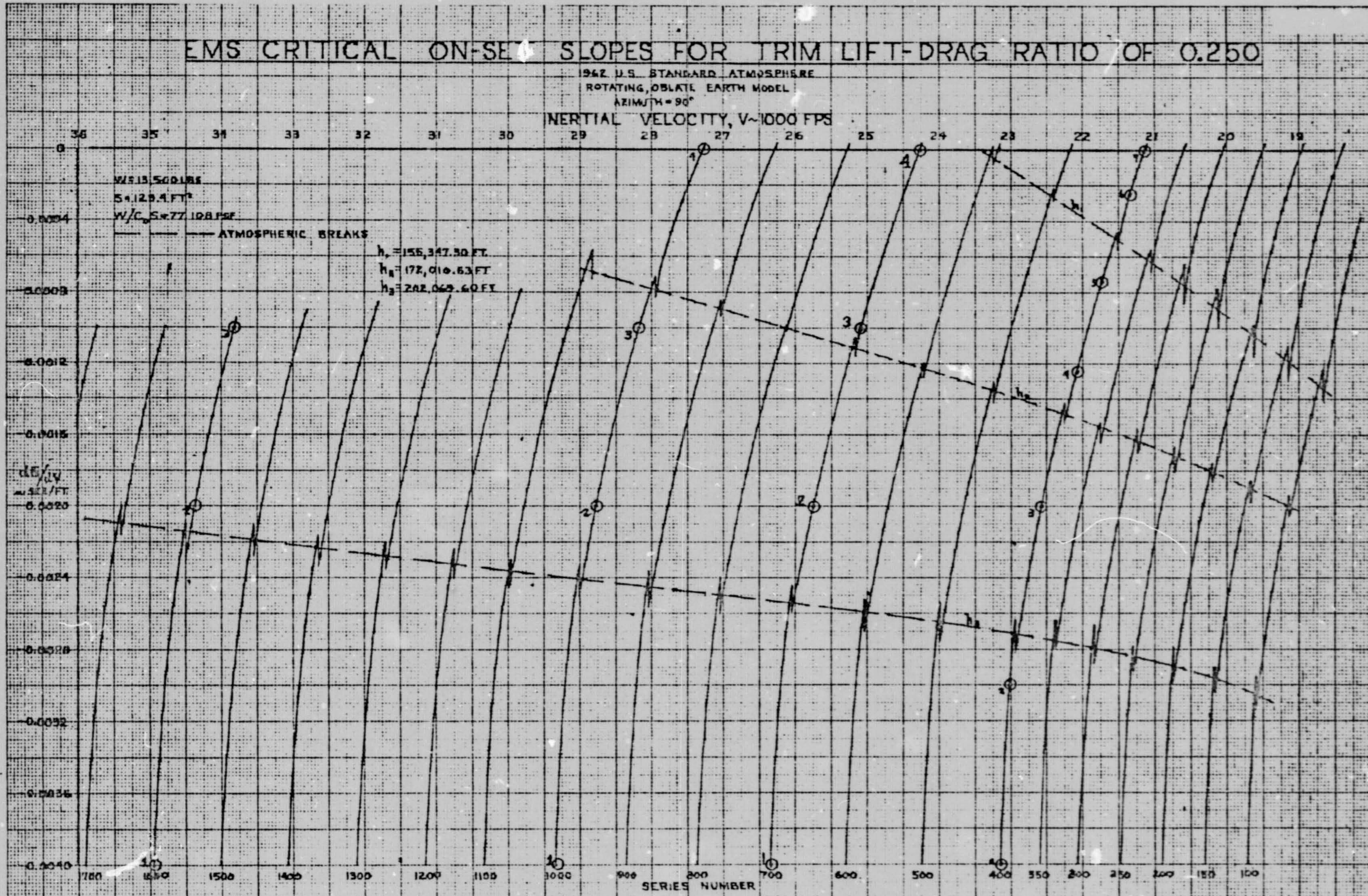


Figure 4. - dG/dV vs velocity for loci of G on-set limiting flight conditions (L/D = 0.250)

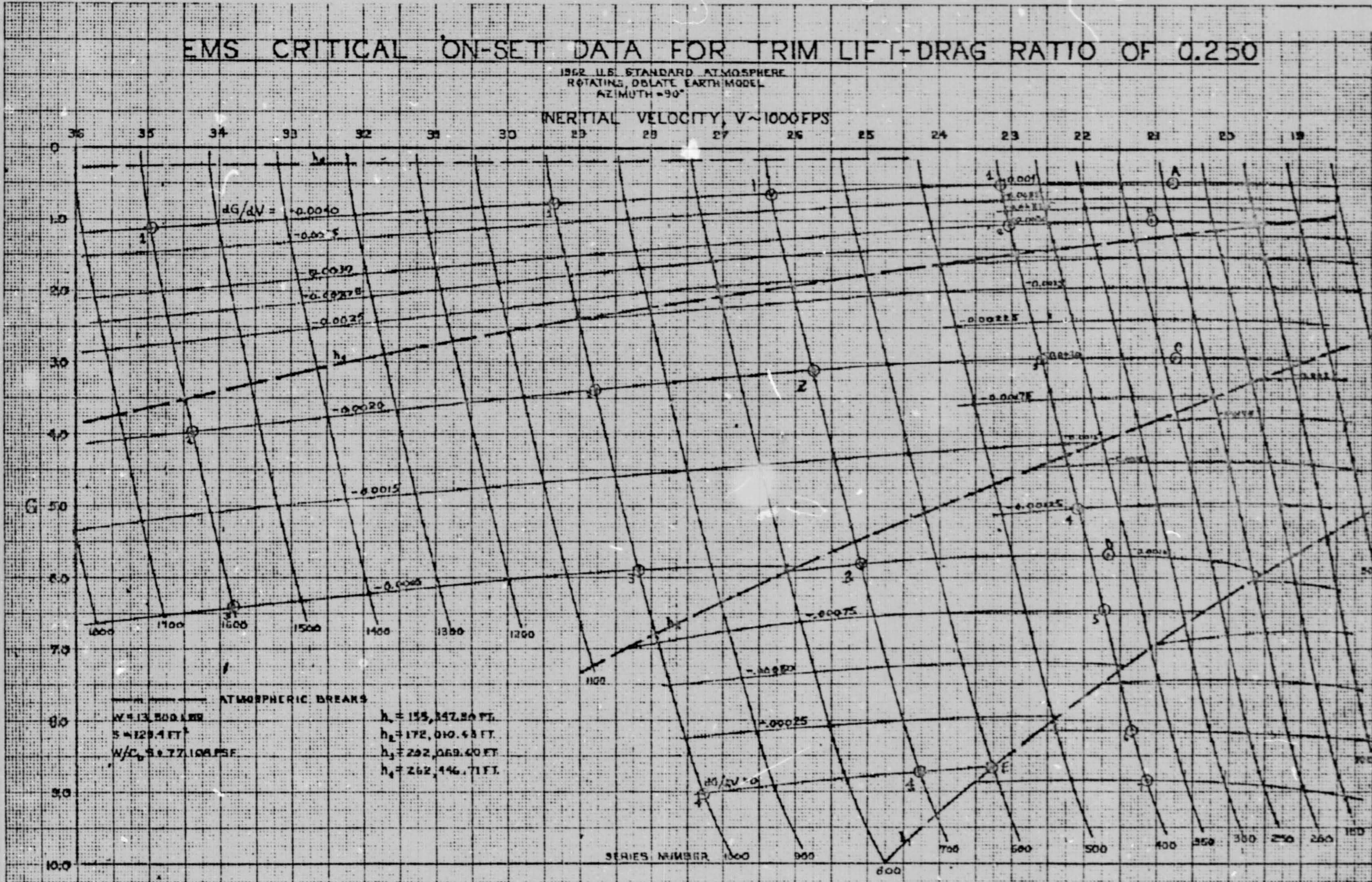


Figure 5. - G vs velocity and values of constant dG/dV for loci of G on-set limiting flight conditions (L/D = 0.250)

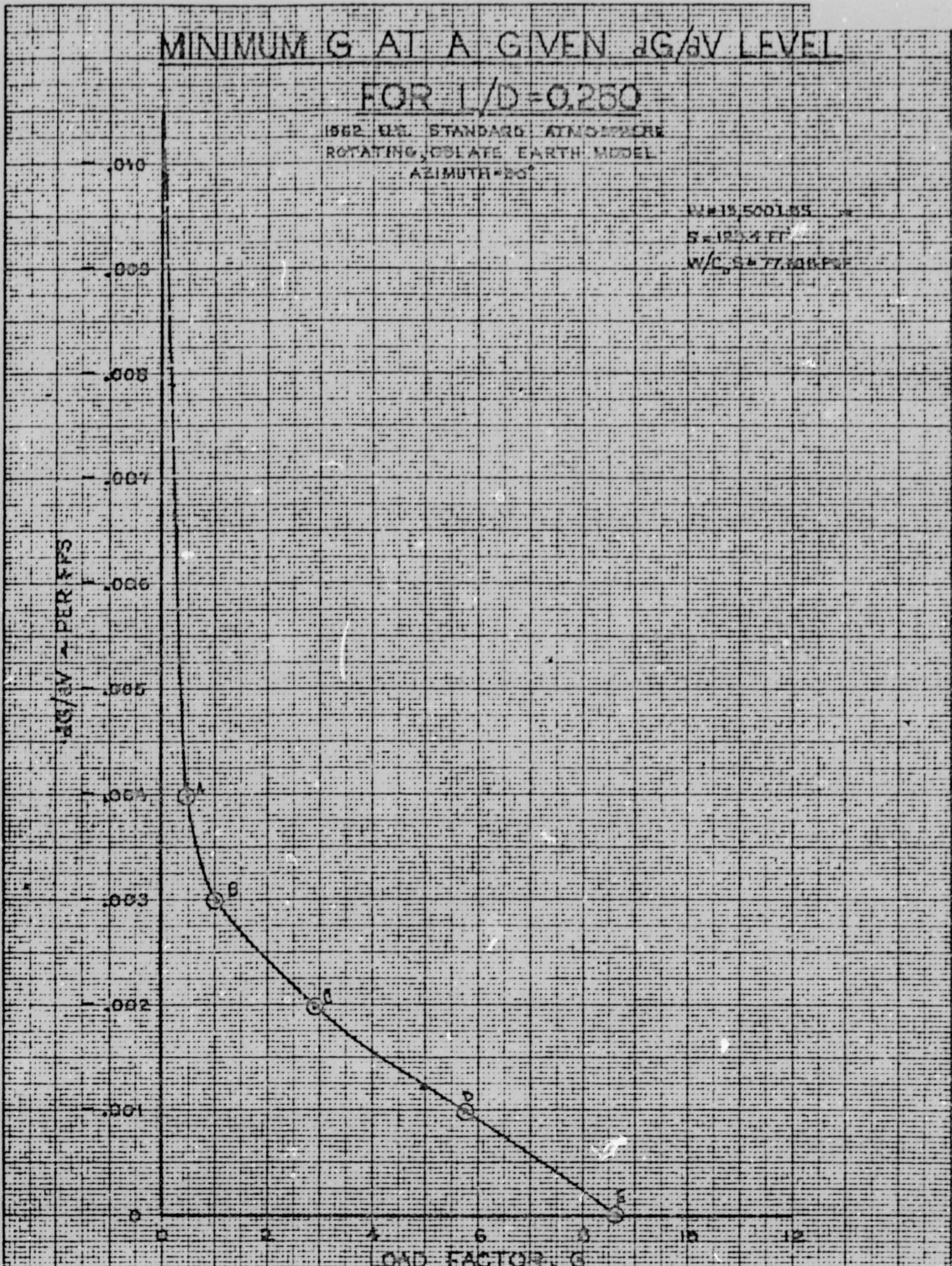


Figure 6. - dG/dV vs minimum G (L/D = 0.250)

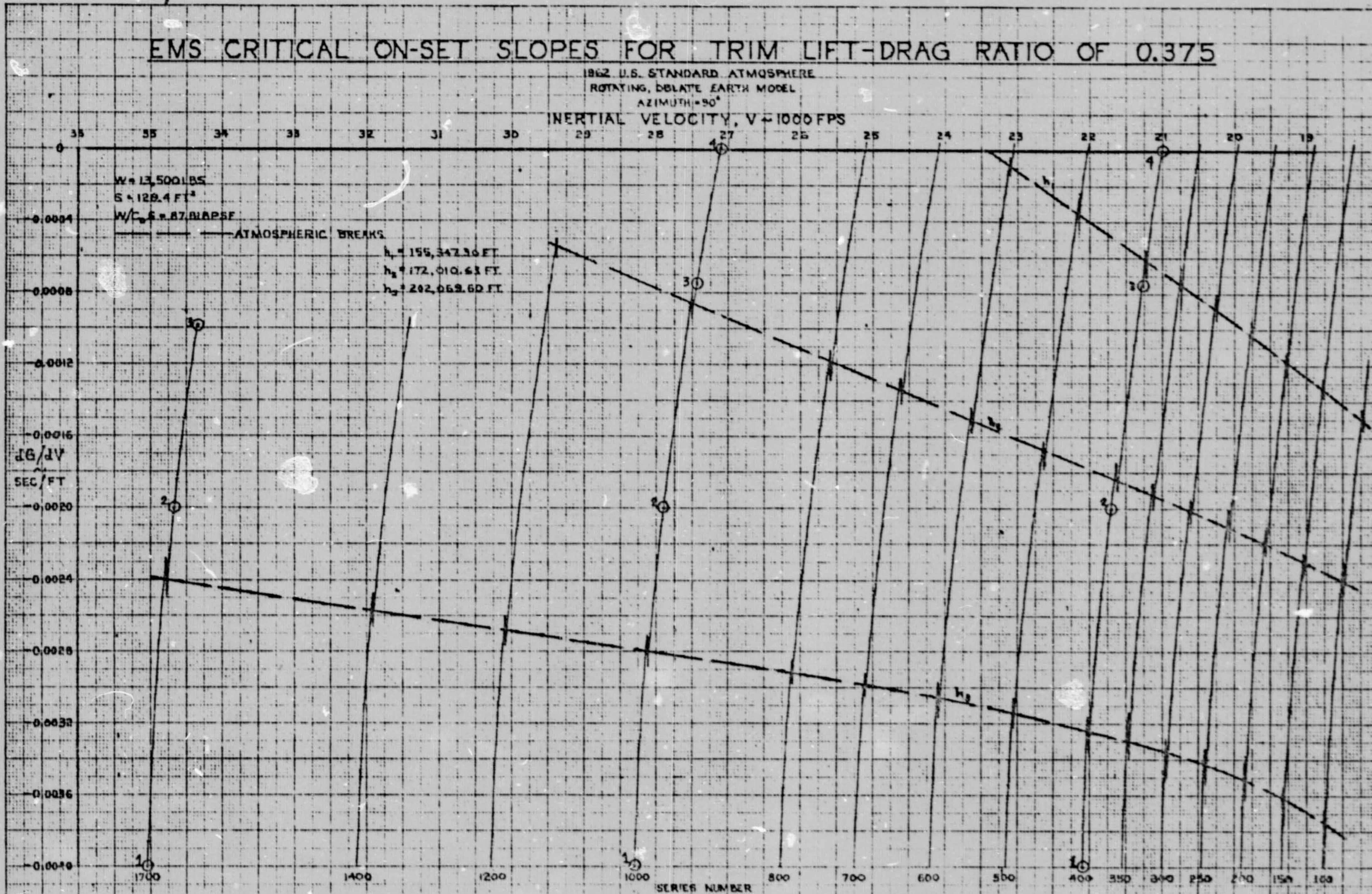


Figure 7. - dG/dV vs velocity for loci of G on-set limiting flight conditions (L/D = 0.375)

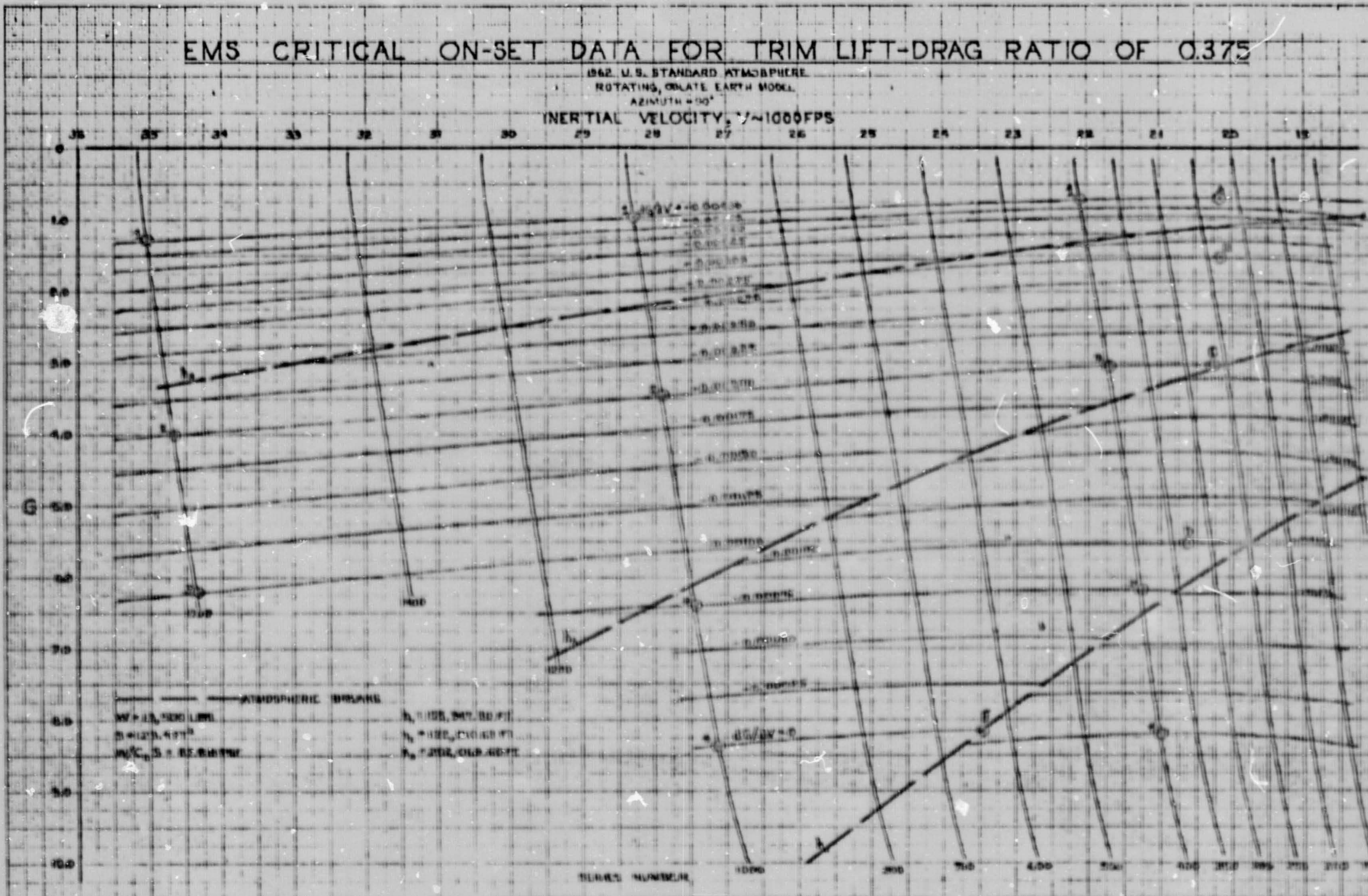


Figure [illegible]. - G vs velocity and values of constant dG/dV for loci of G on-set limiting flight conditions (L/D = 0.375)

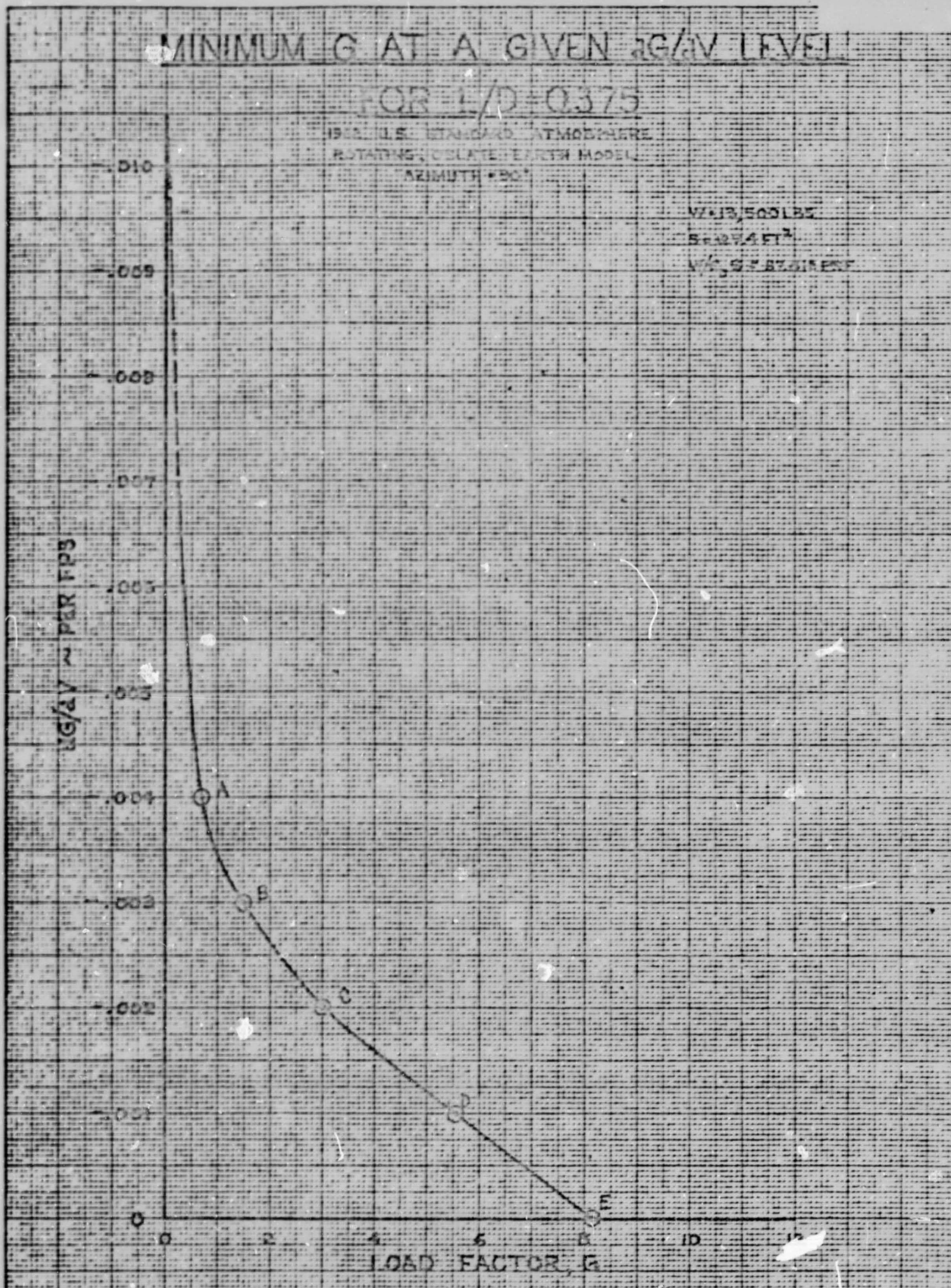


Figure 9. - dG/dV vs minimum G (L/D = 0.375)

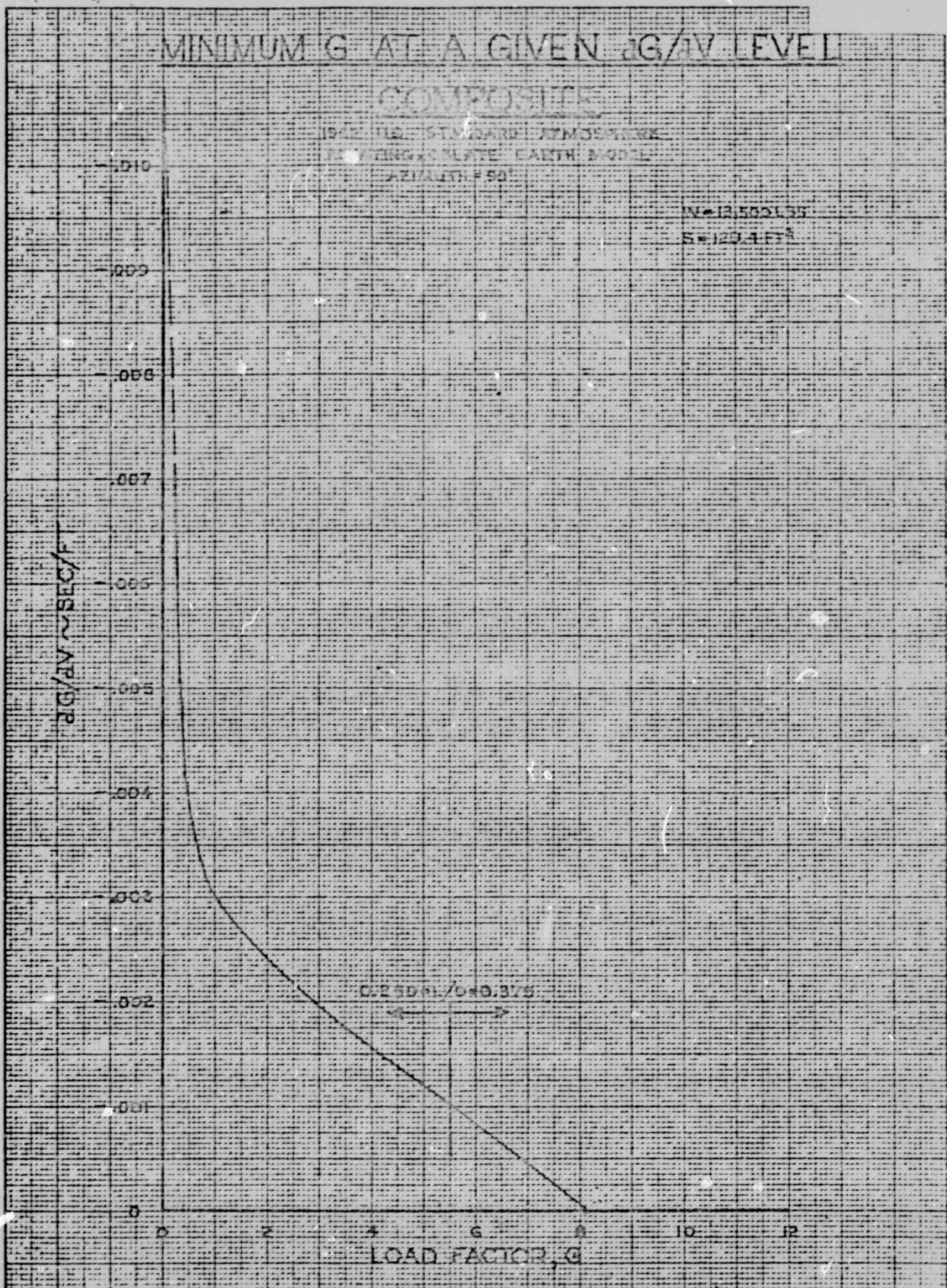


Figure 10. - dG/dV vs minimum G ($0.250 \leq L/D \leq 0.375$)

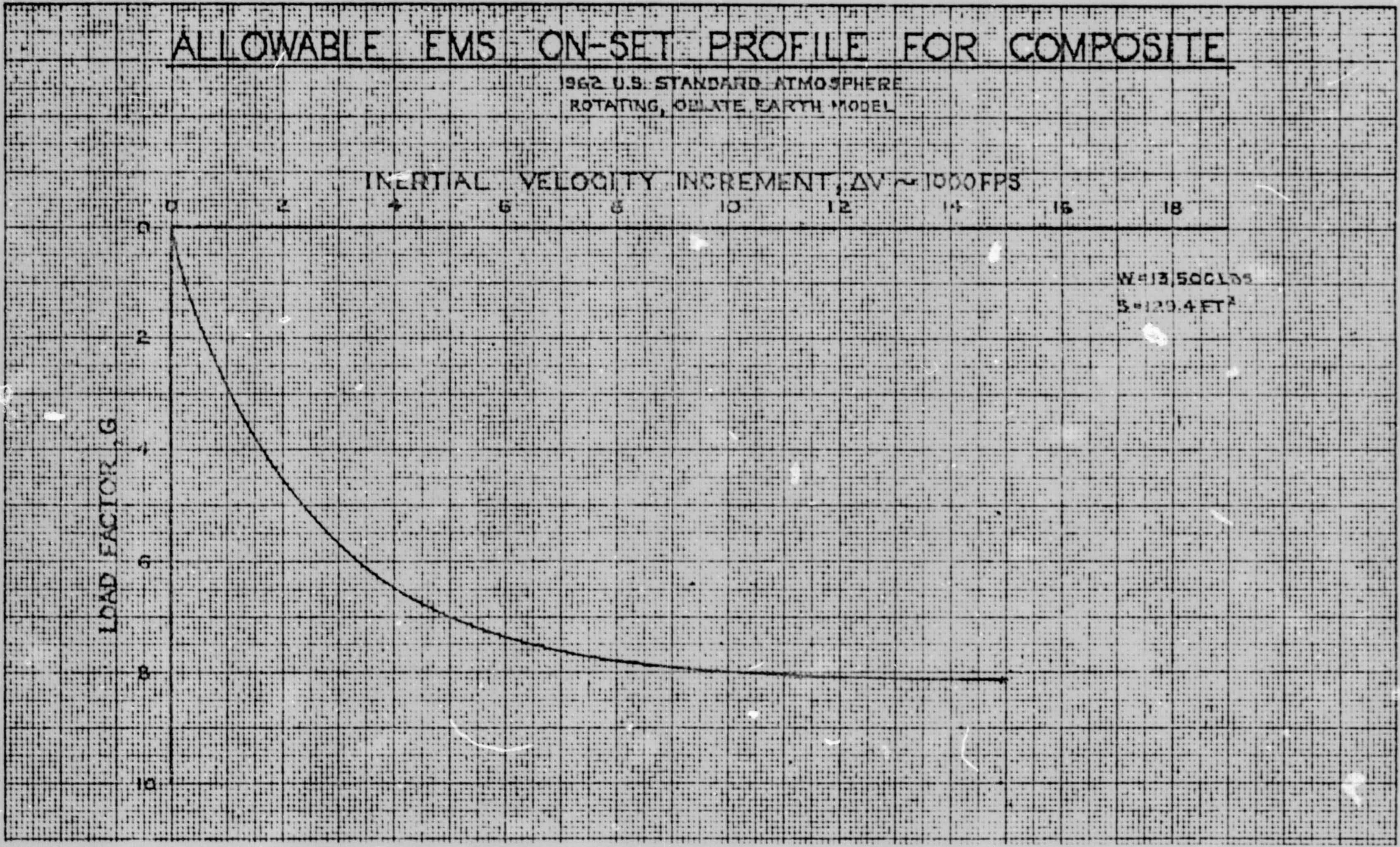


Figure 11. - Final form of G on-set limit lines displayed by the EMS

DESIGN LIMIT: 3500 NM MAXIMUM RANGE

DESIGN LIMIT PROTECTED FOR VIOLATIONS WITH FULL LIFTUP

PILOT RESPONSE TIME = 2 SEC

TIME FROM LIFTUP TO LIFT DOWN = 14.5 SEC

VEHICLE WEIGHT = 13,500 LB

$\pm 3\sigma$ DENSITY DEVIATIONS OF THE 1962 U.S. STANDARD ATMOSPHERE

$$L/D = \begin{cases} 0.375 \\ 0.250 \end{cases}$$

Figure 12. - Analytical model for 3500 nm range limit lines

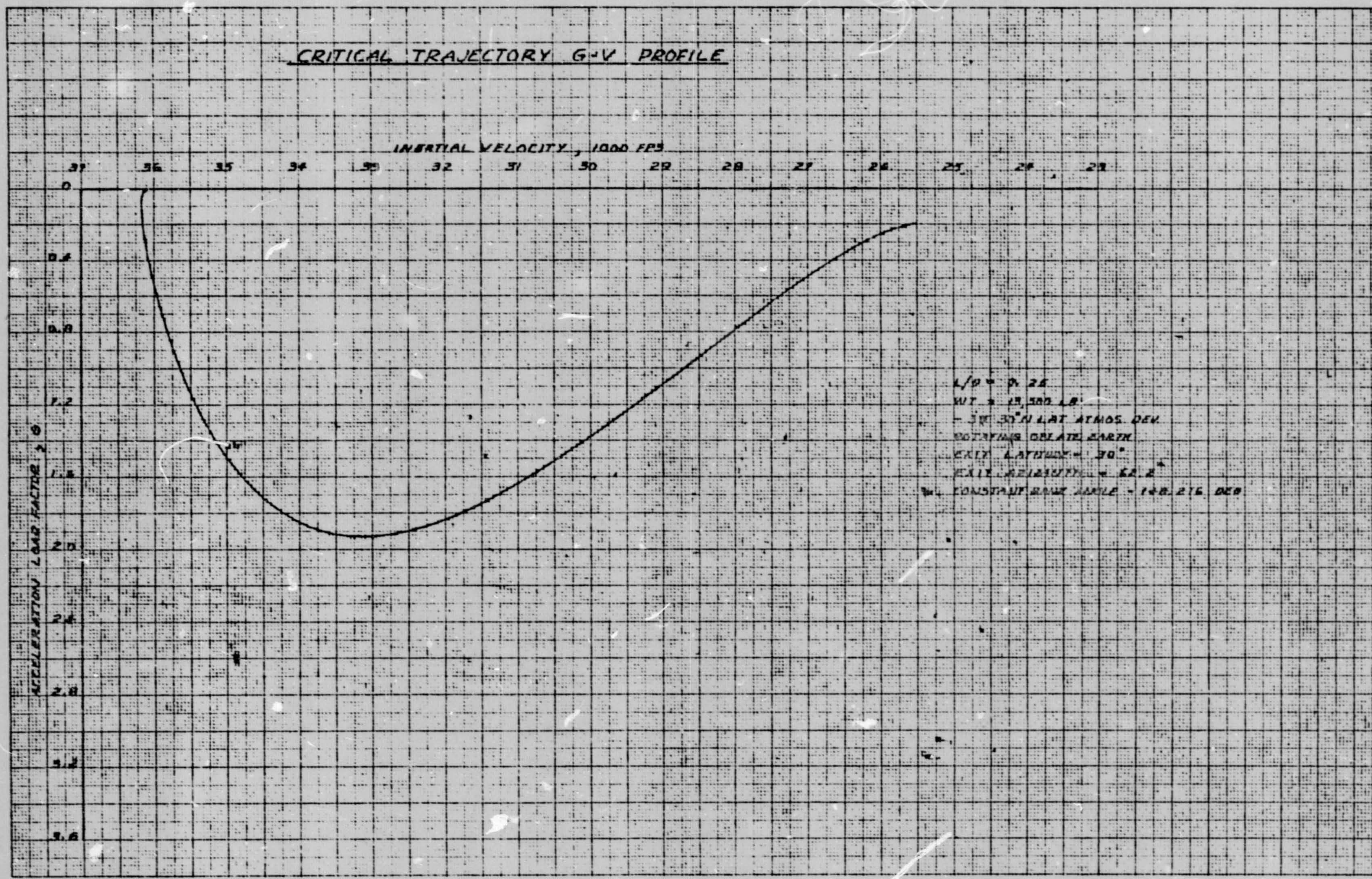


Figure 13. - G vs velocity profile of the critical trajectory (L/D = 0.250)

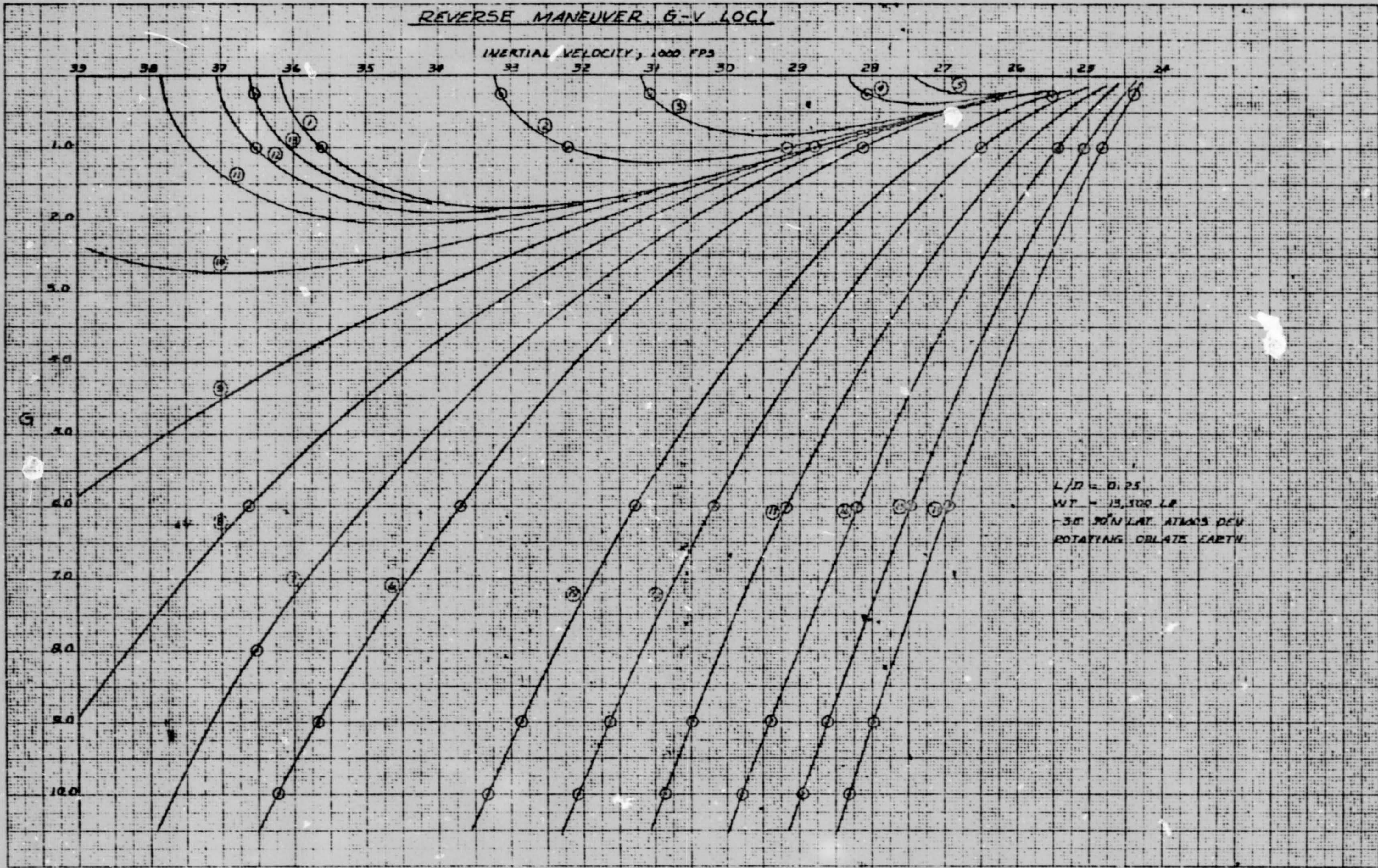


Figure 14. - G vs velocity for loci of range limiting flight conditions (L/D = 0.250)

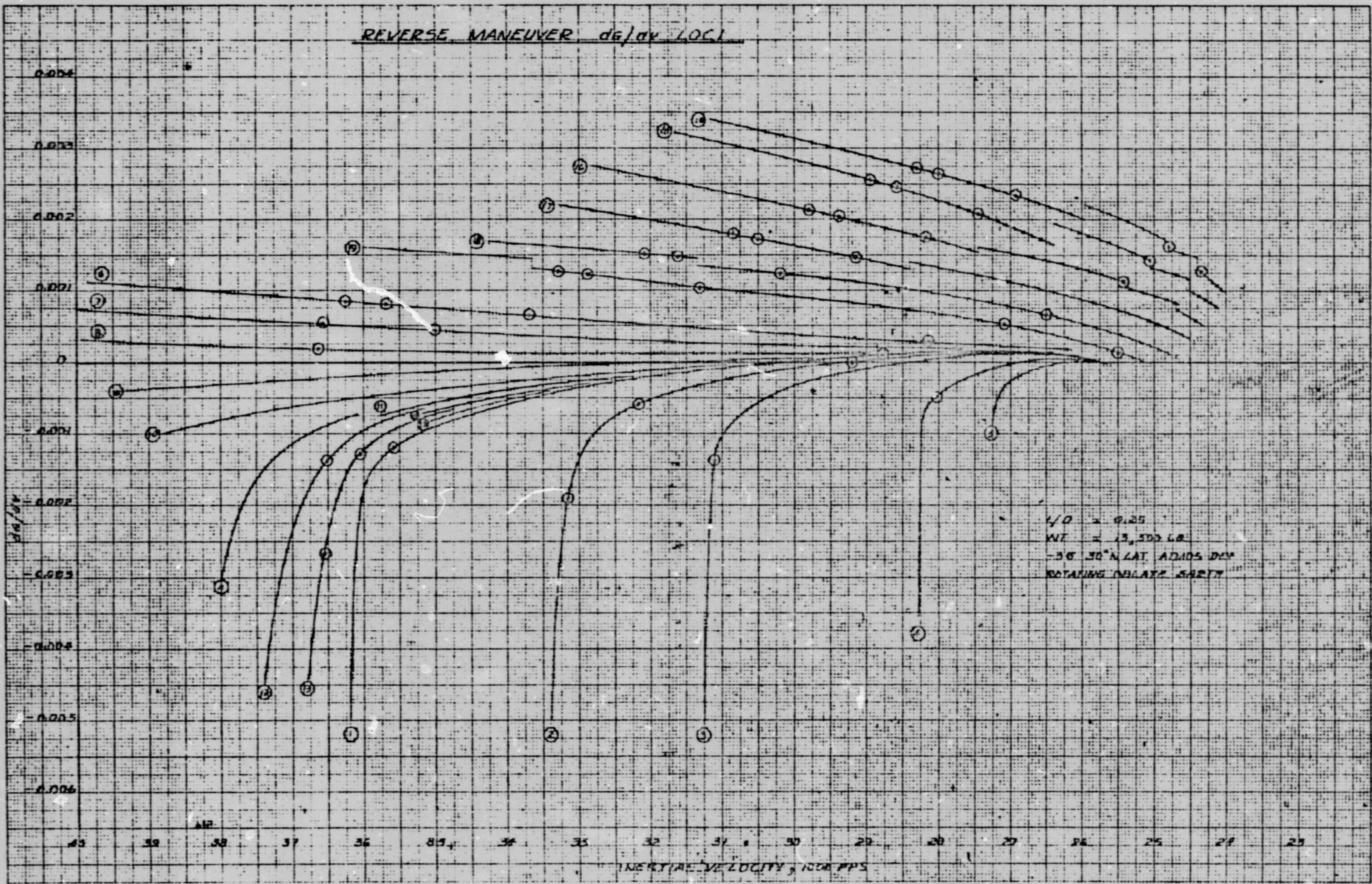


Figure 15. - dG/dV vs velocity for loci of range limiting flight conditions (L/D = 0.250)

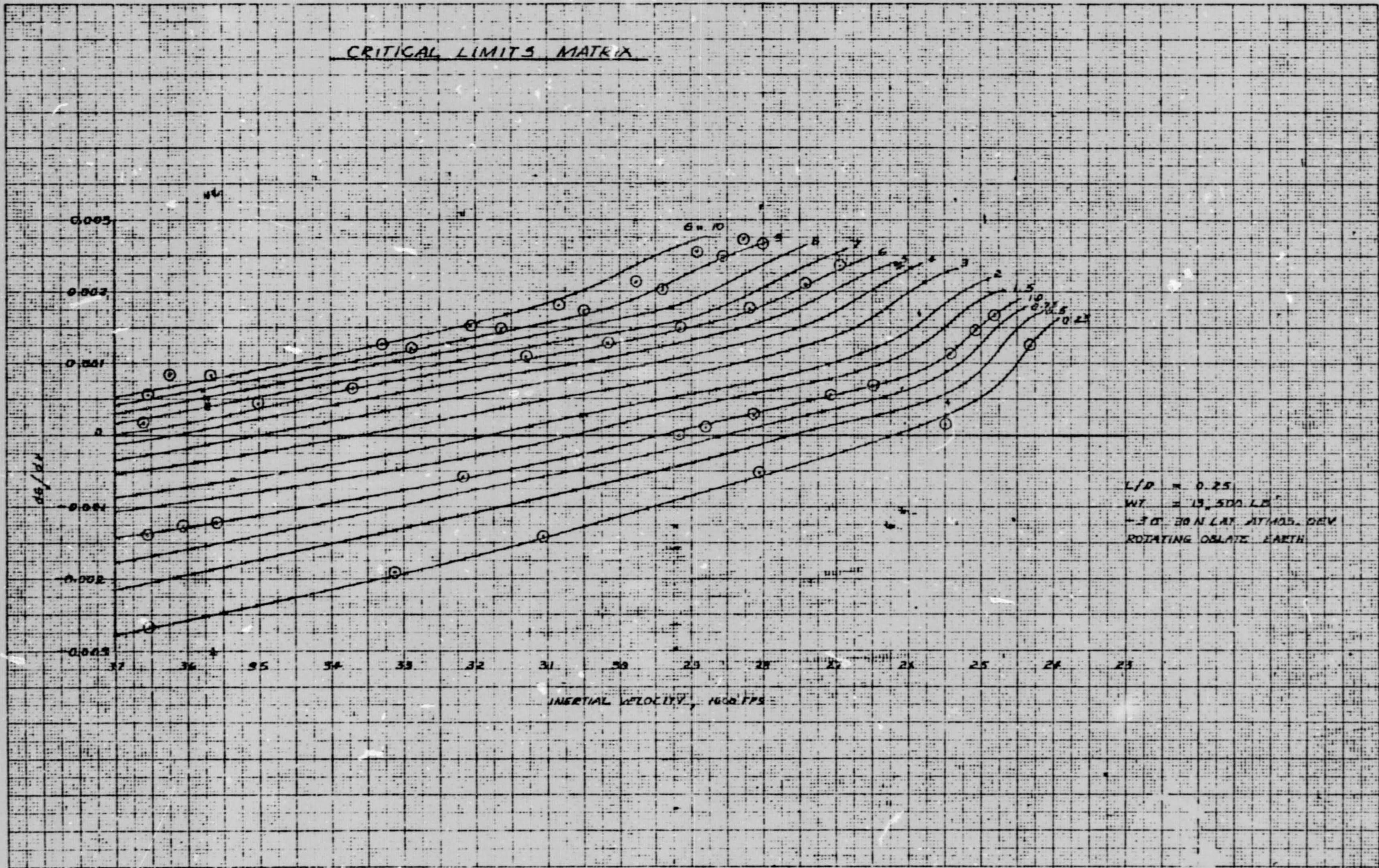


Figure 16. - dG/dV vs velocity for values of constant G (L/D = 0.250)

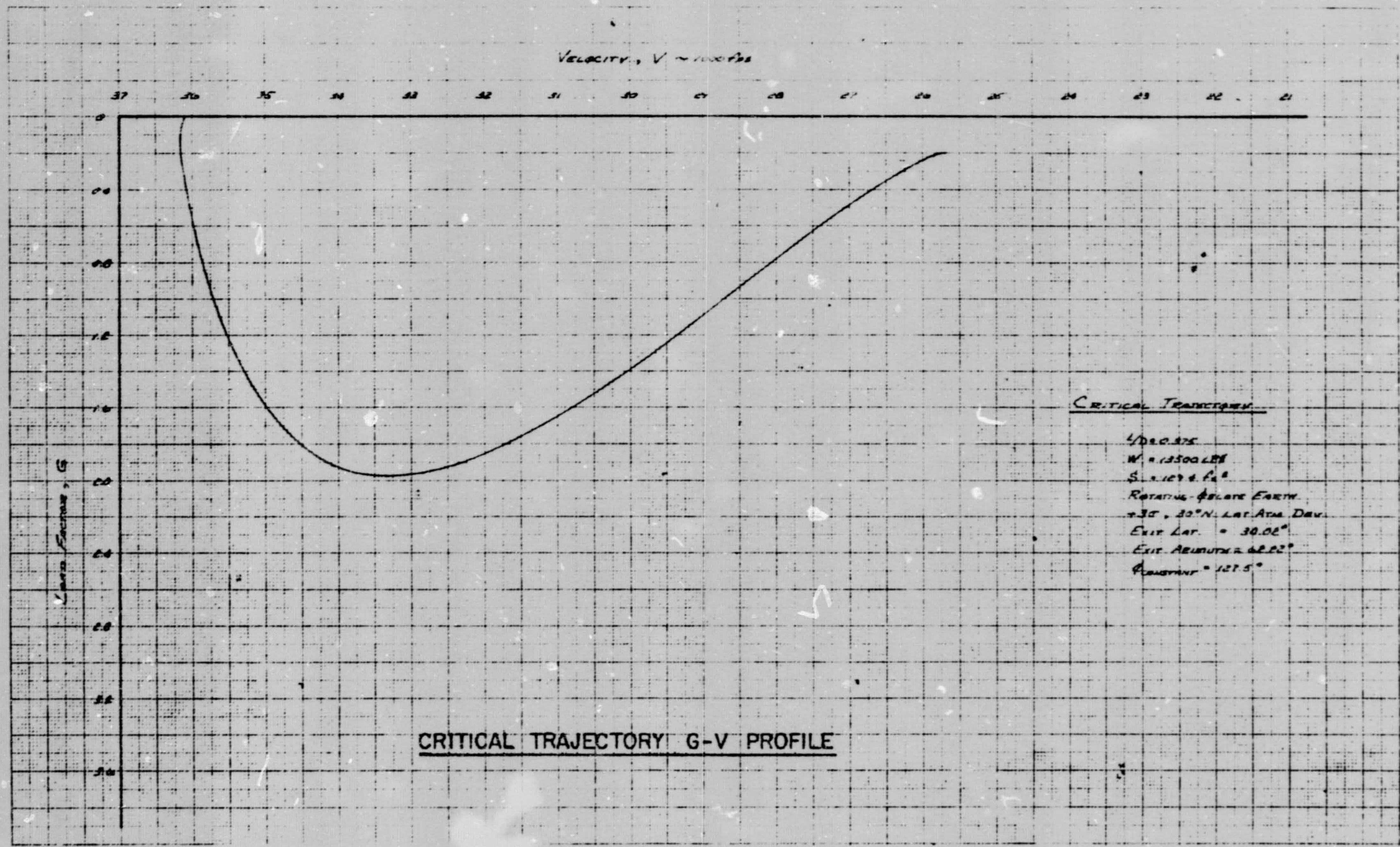


Figure 17. - G vs velocity profile of the critical trajectory (L/D = 0.375)

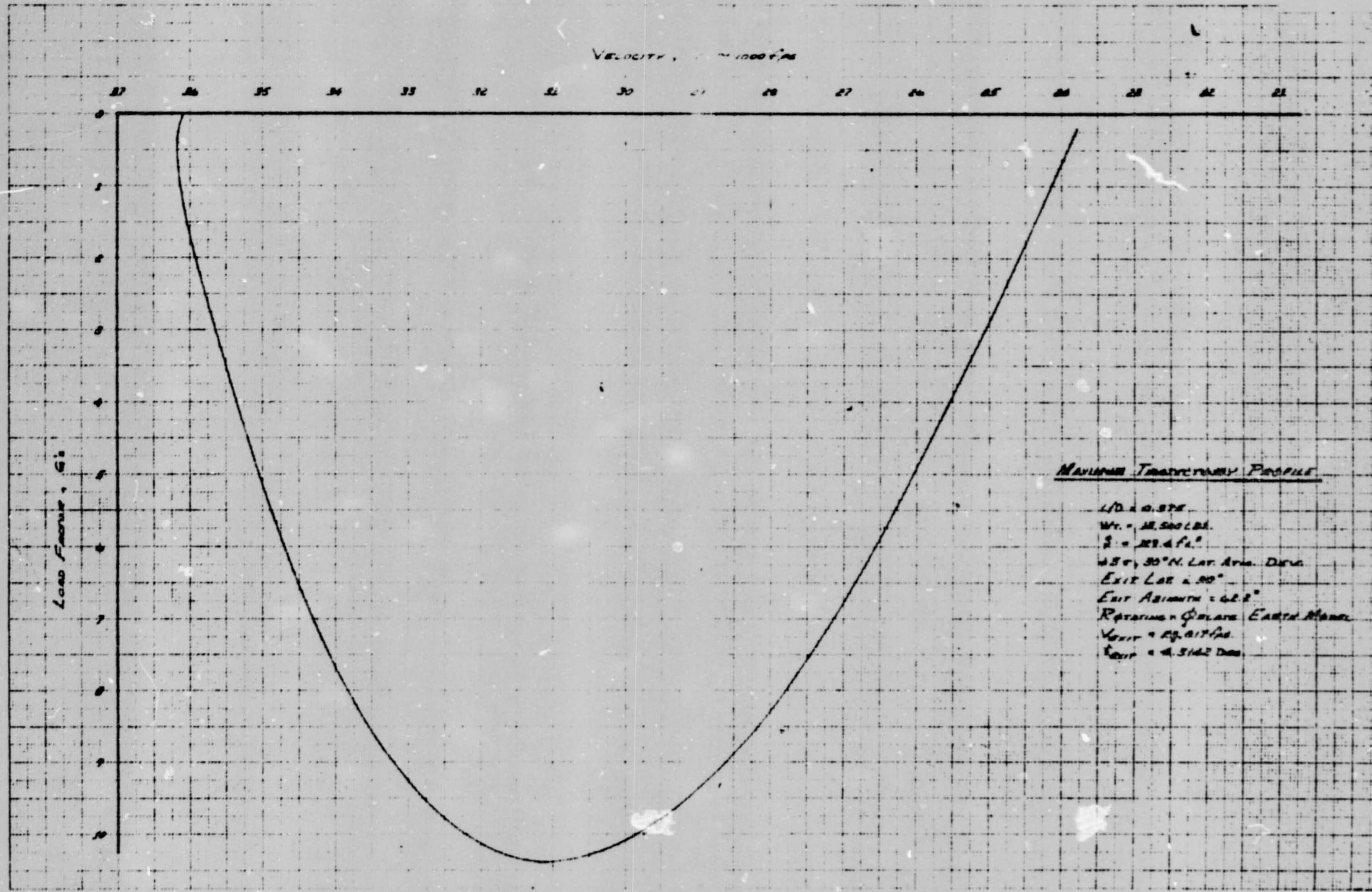

Figure 18.- G vs velocity profile of the maximum trajectory (L/D = 0.375)

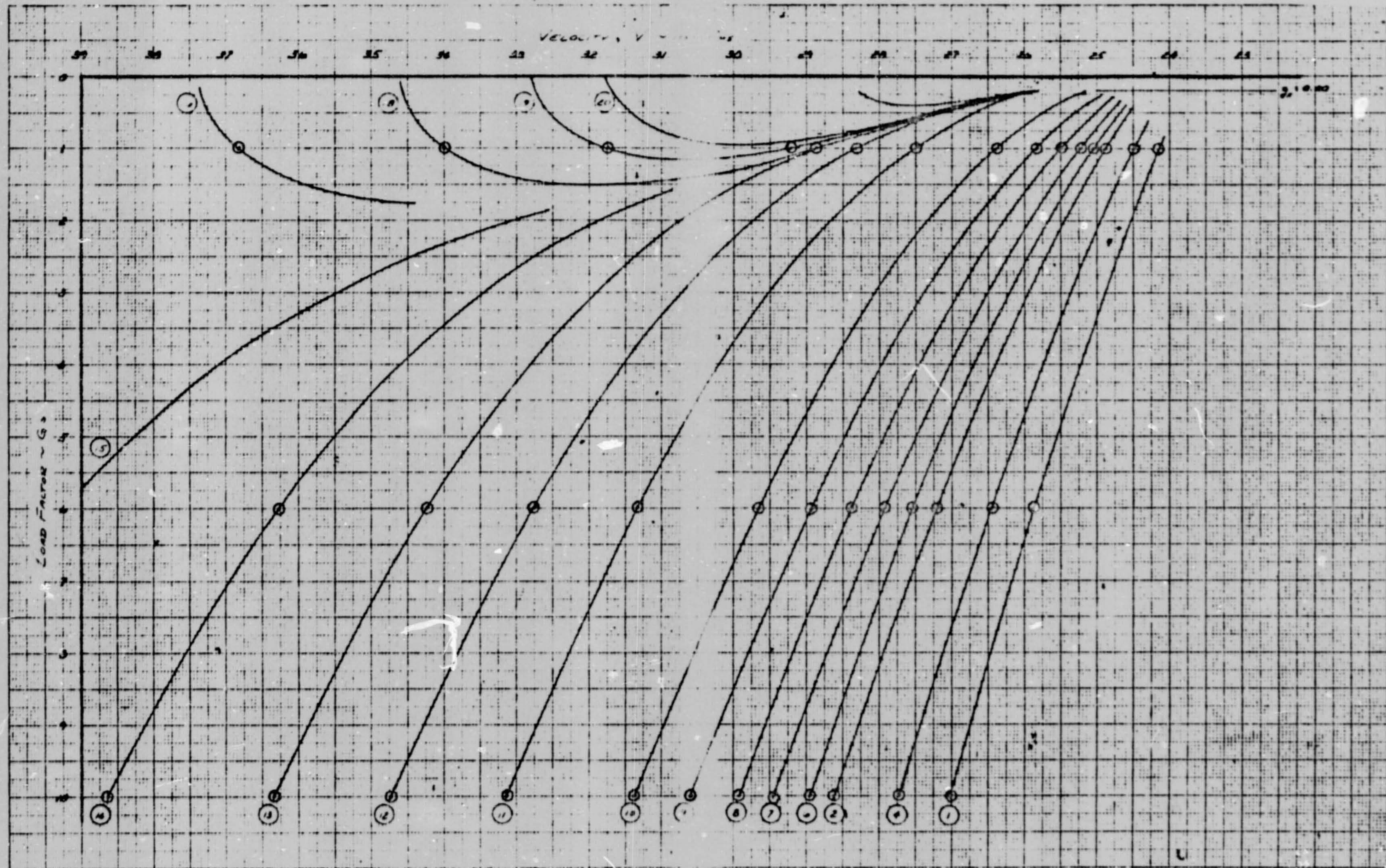

Figure 19. - G vs velocity for loci of range limiting flight conditions (L/D = 0.375)

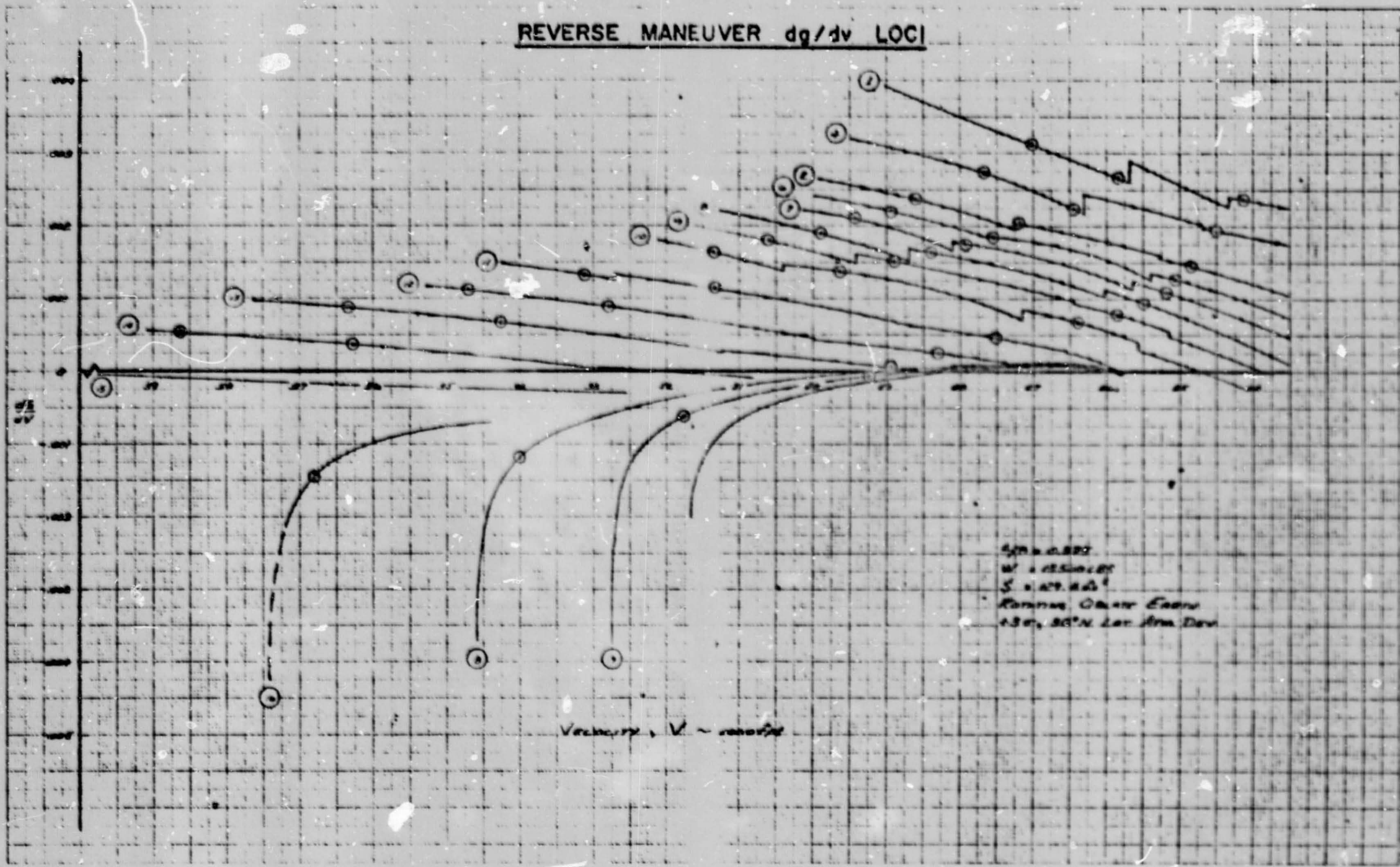


Figure 20. - dG/dV vs velocity for loci of range limiting flight conditions (L/D = 0.375)

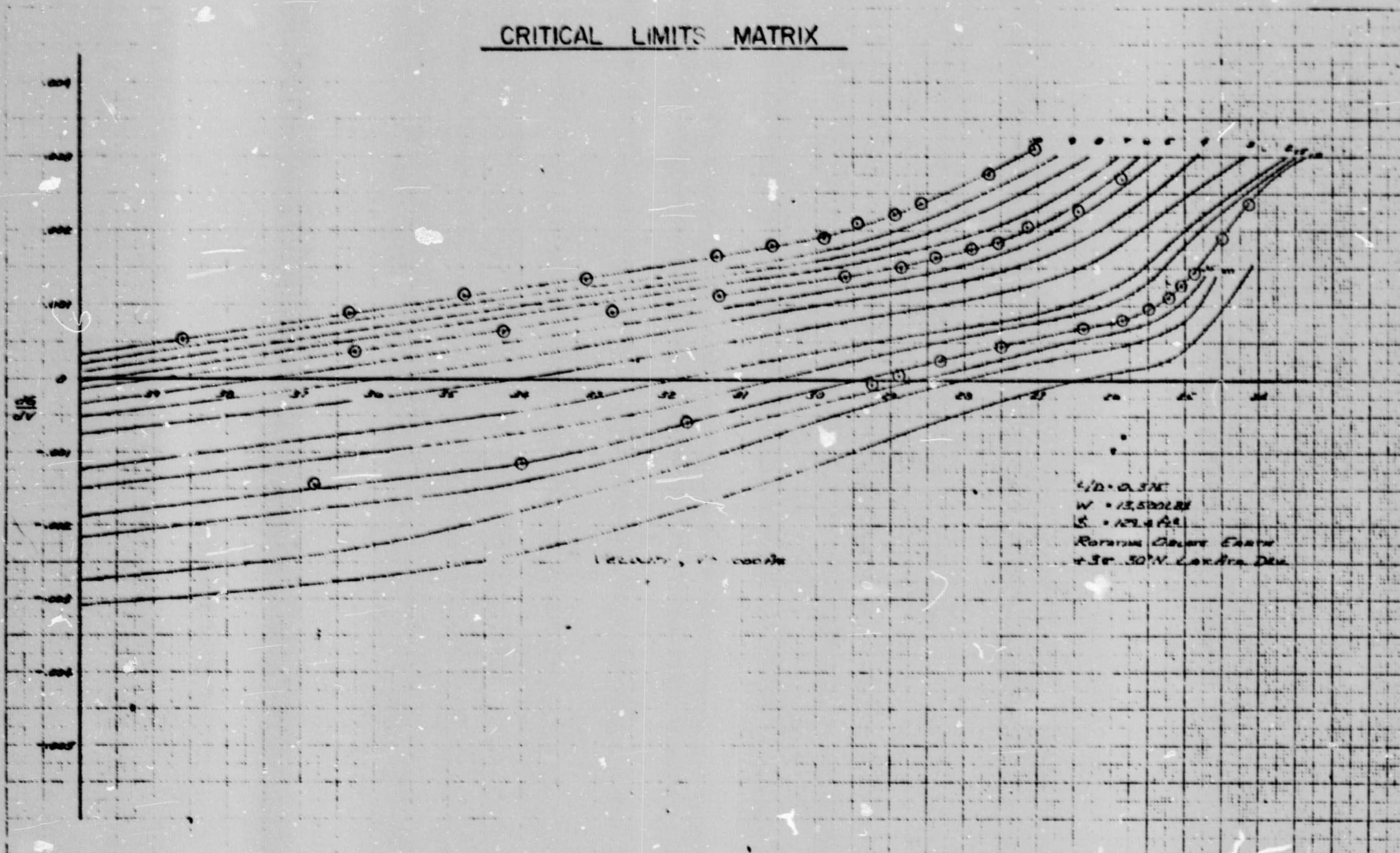


Figure 21. - dG/dV vs velocity for values of constant G (L/D = 0.375)

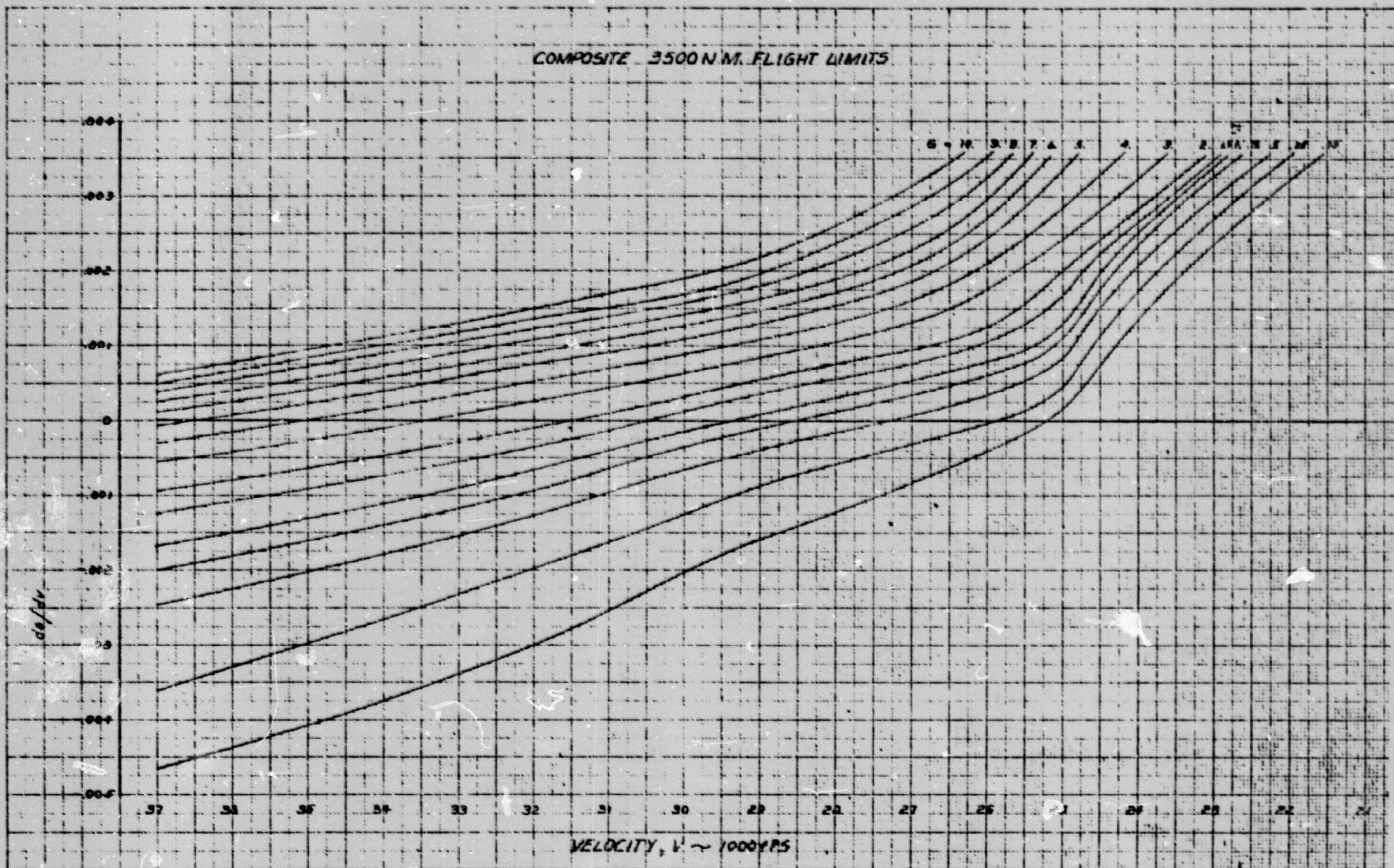


Figure 22. - dG/dV vs velocity for loci of range limiting flight conditions ($0.250 \leq L/D \leq 0.375$)

DESIGN LIMITS ARE:

0.2G MINIMUM

3500 NM MAXIMUM RANGE

DESIGN LIMITS PROTECTED FOR VIOLATIONS WITH FULL LIFT UP

PILOT RESPONSE TIME = 2 SEC

TIME FROM LIFT UP TO LIFT DOWN = 14.5 SEC

VEHICLE WEIGHT = 13,500 LBS

$\pm 3\sigma$ DENSITY DEVIATIONS OF THE 1962 U. S. STANDARD ATMOSPHERE

$$L/D = \begin{cases} 0.375 \\ 0.250 \end{cases}$$

Figure 23. - Analytical model for skip limit lines

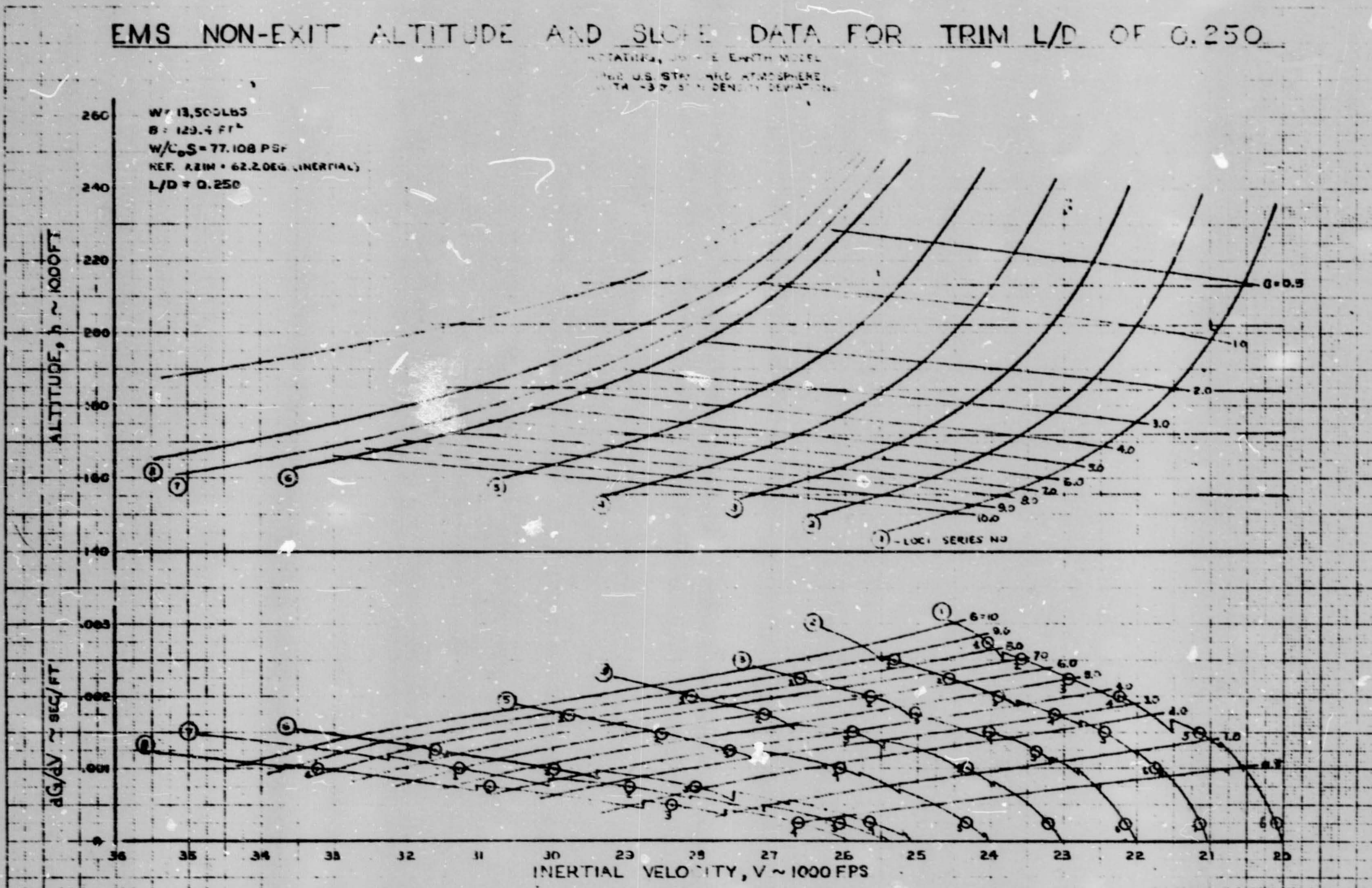


Figure 24(a). - Altitude and dG/dV vs velocity with values of constant G for loci of skip limiting flight conditions (L/D = 0.250)

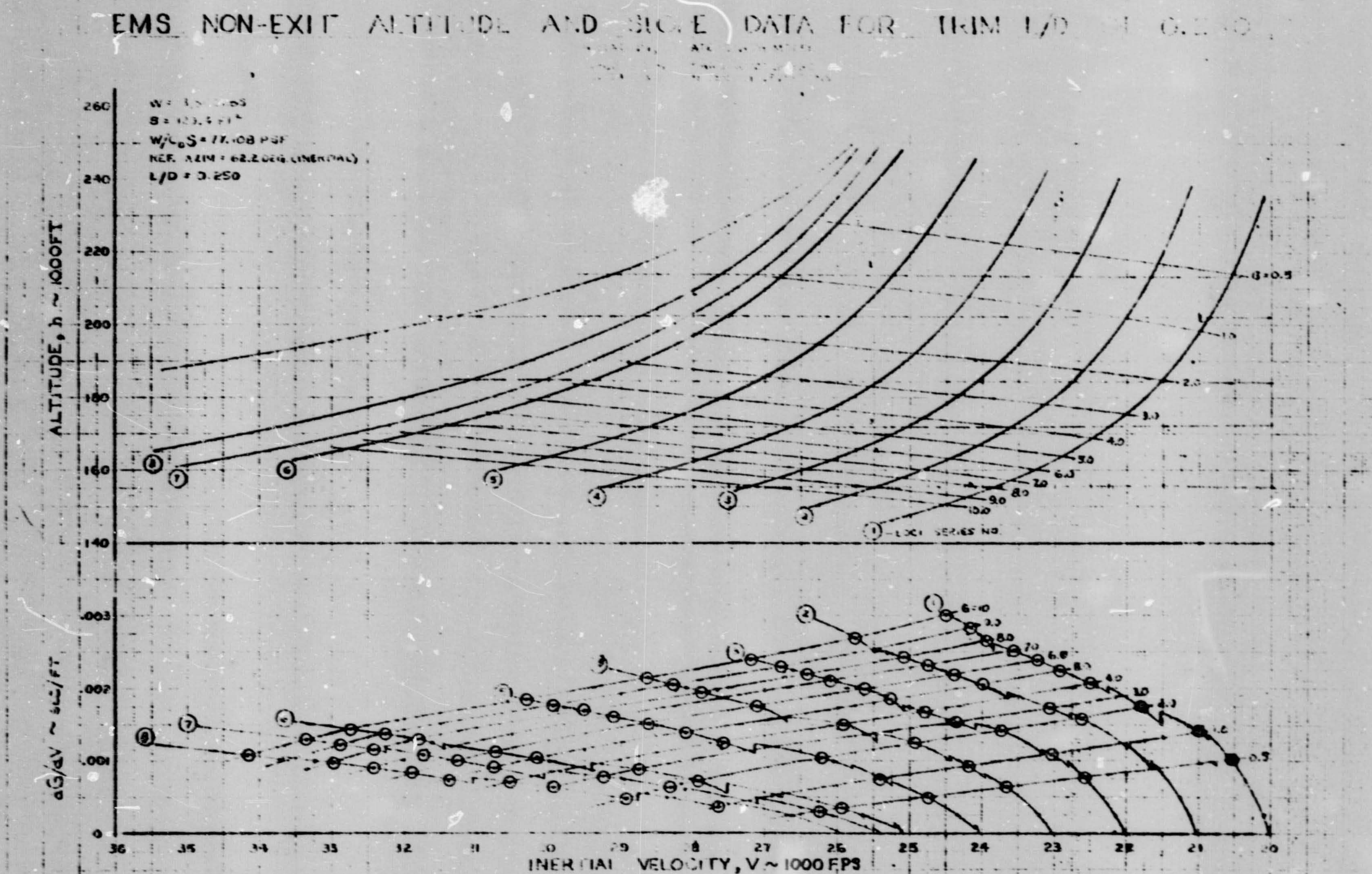


Figure 24(b). - Altitude and dG/dV vs velocity with values of constant G for loci of skip limiting flight conditions (L/D = 0.250)

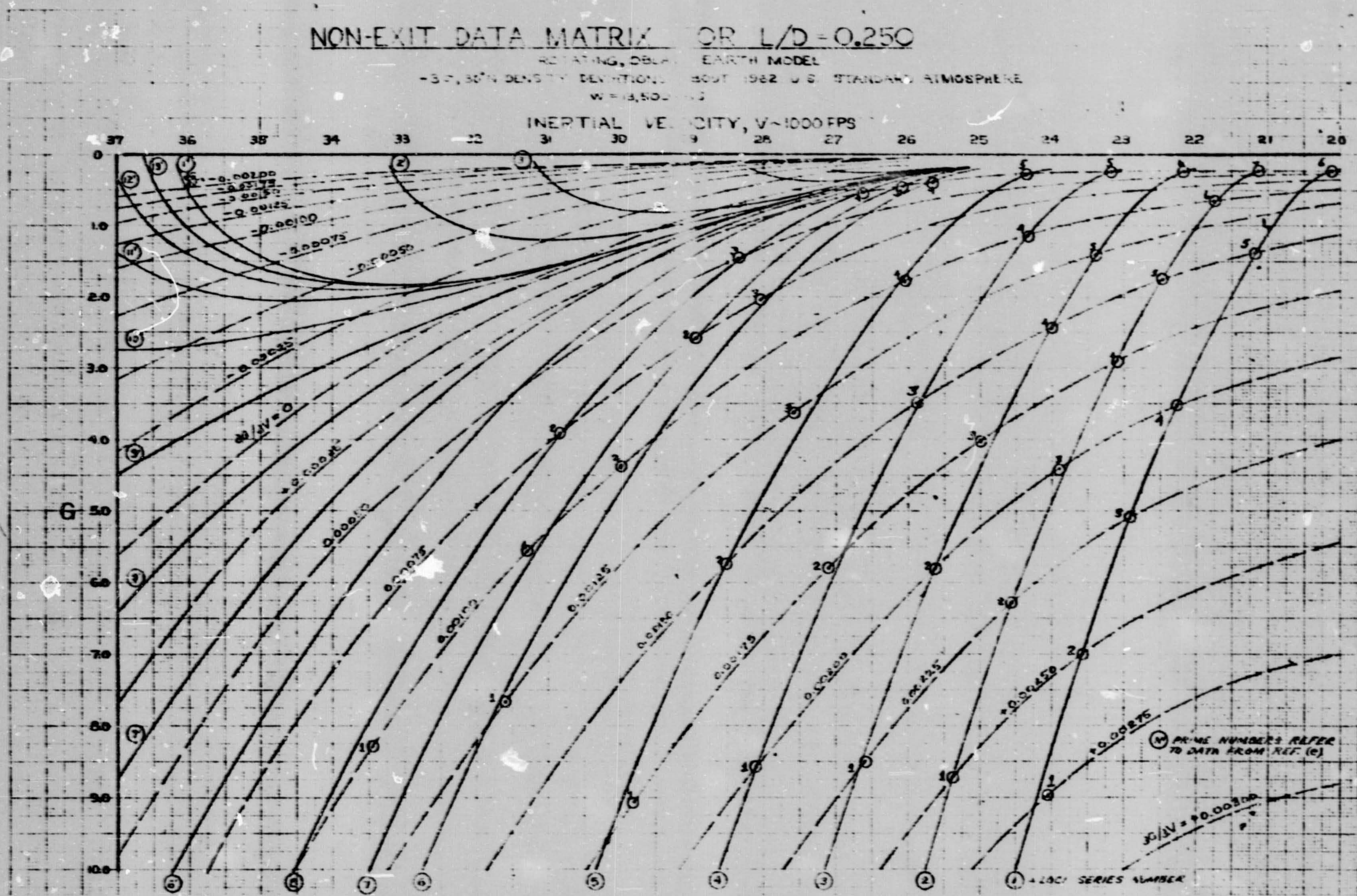


Figure 25(a). - G vs velocity and values of constant dG/dV for loci of skip limiting flight conditions (L/D = 0.250)

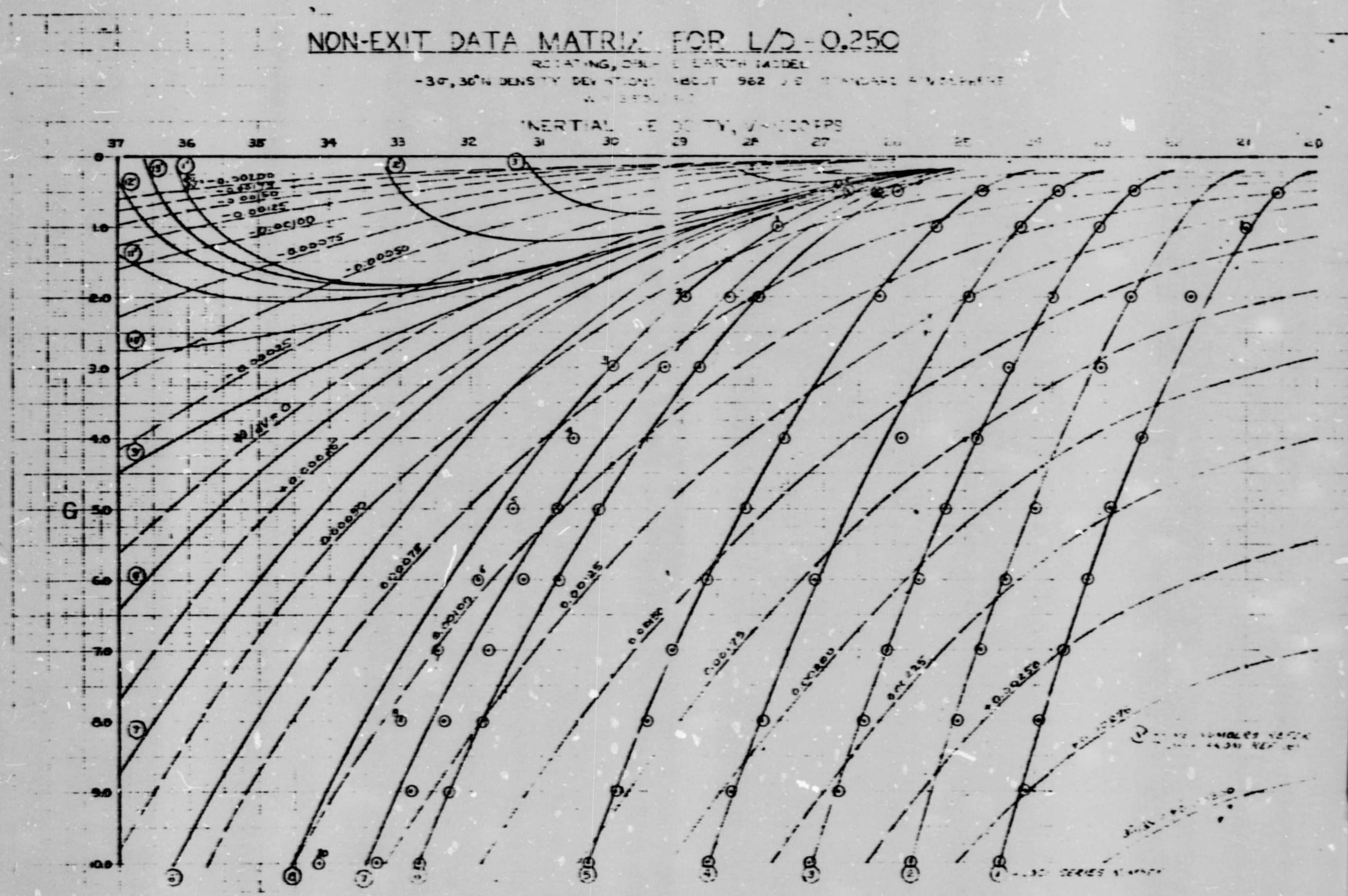


Figure 25(b). - G vs velocity and values of constant dG/dV for loci of skip limiting flight conditions (L/D = 0.250)

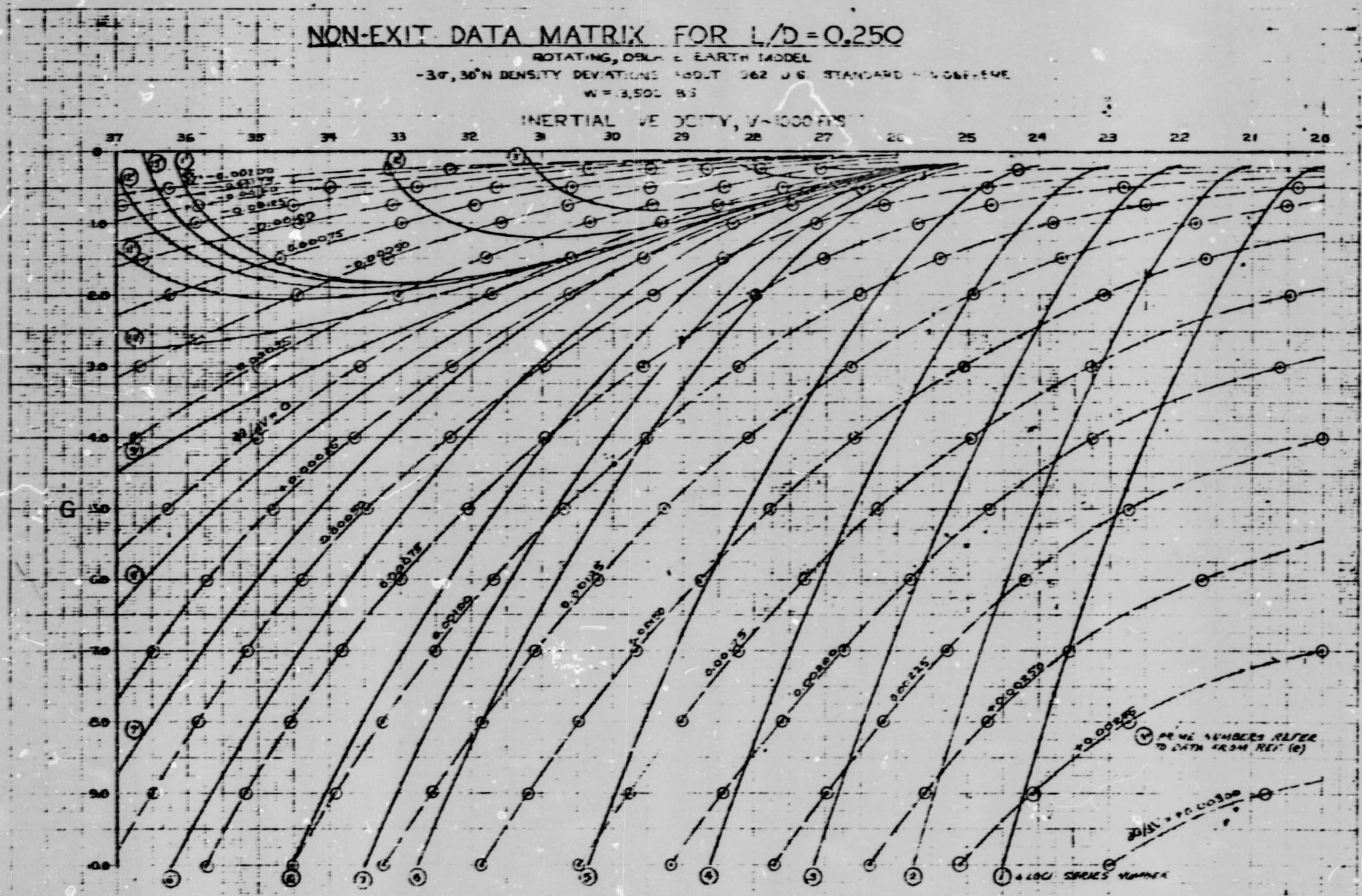


Figure 25(c). - G vs velocity and values of constant dG/dV for loci of skip limiting flight conditions (L/D = 0.250)

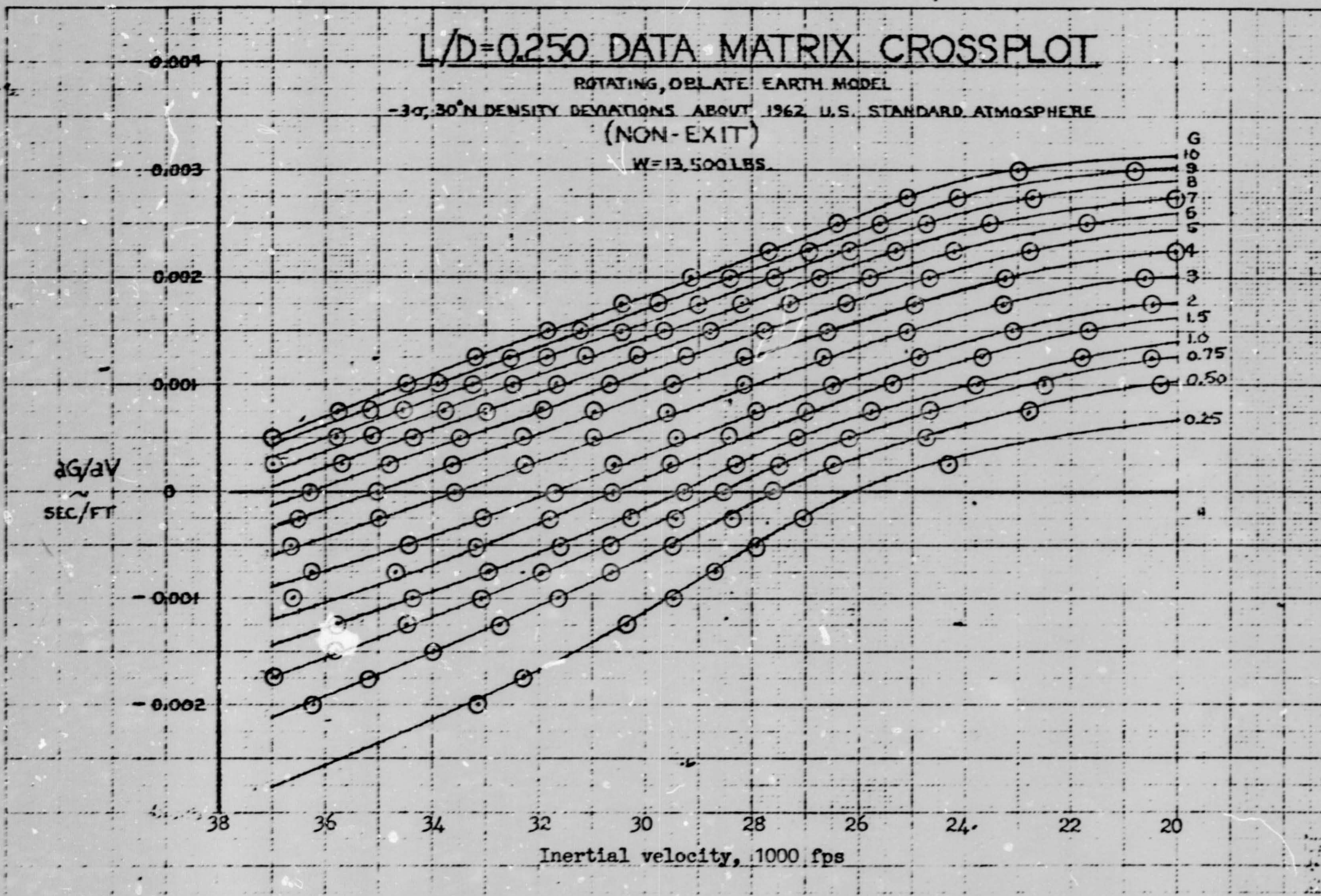


Figure 26. - dG/dV vs velocity for values of constant G (L/D = 0.250)

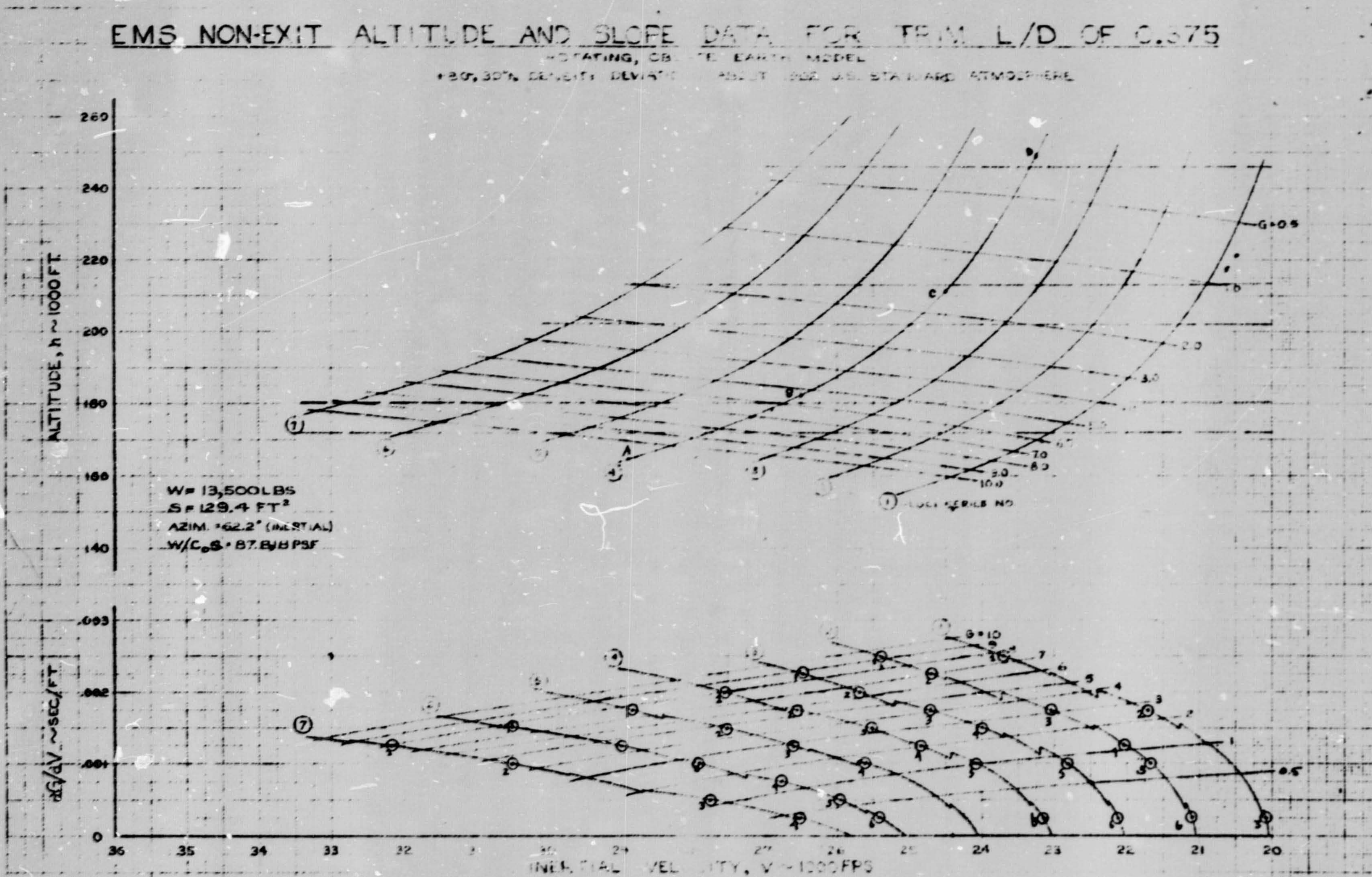


Figure 27(a). - Altitude and dG/dV vs velocity with values of constant G for loci of skip limiting flight conditions (L/D = 0.375)

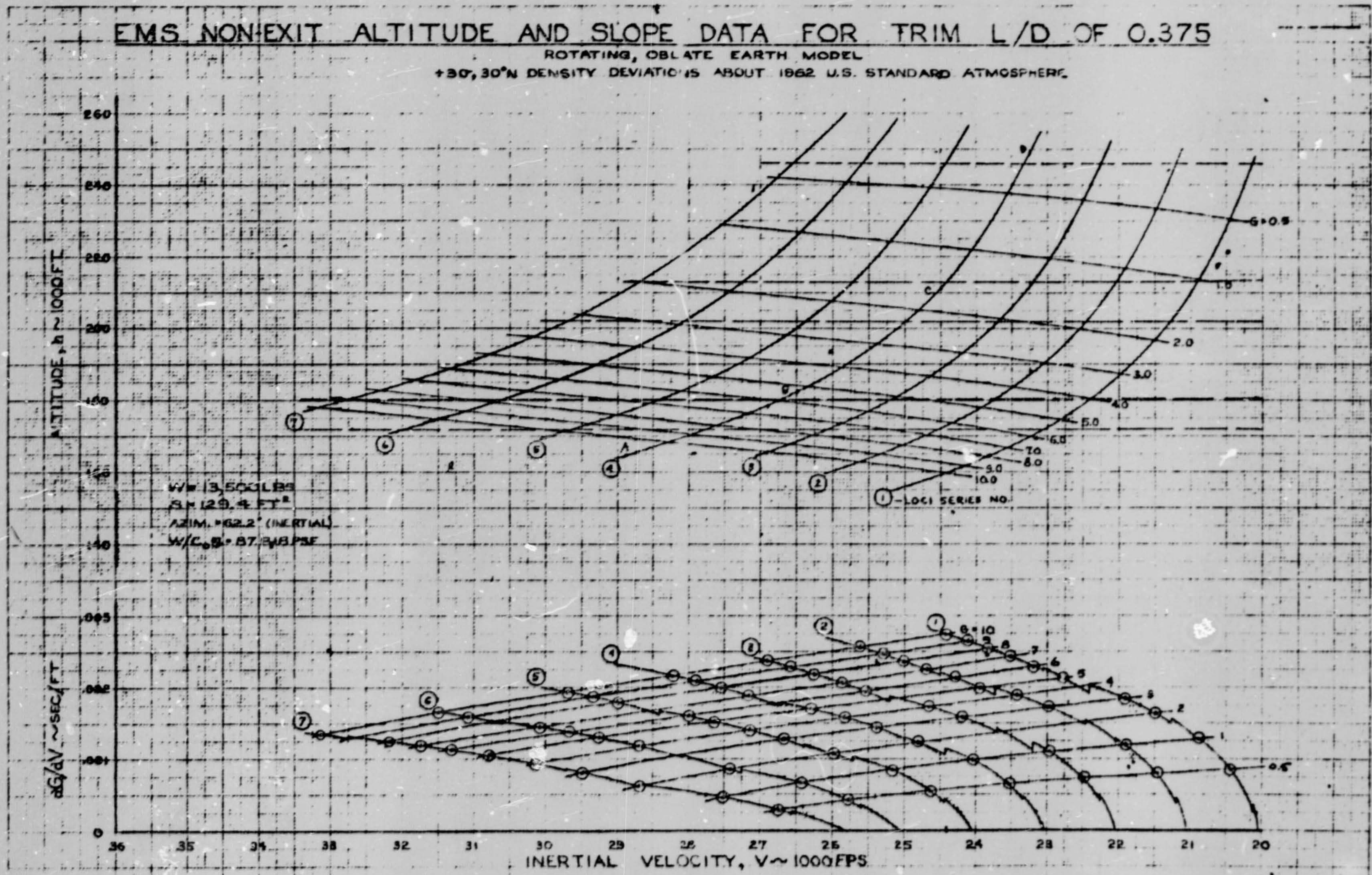


Figure 27(b). - Altitude and dG/dV vs velocity with values of constant G for loci of skip limiting flight conditions (L/D = 0.375)

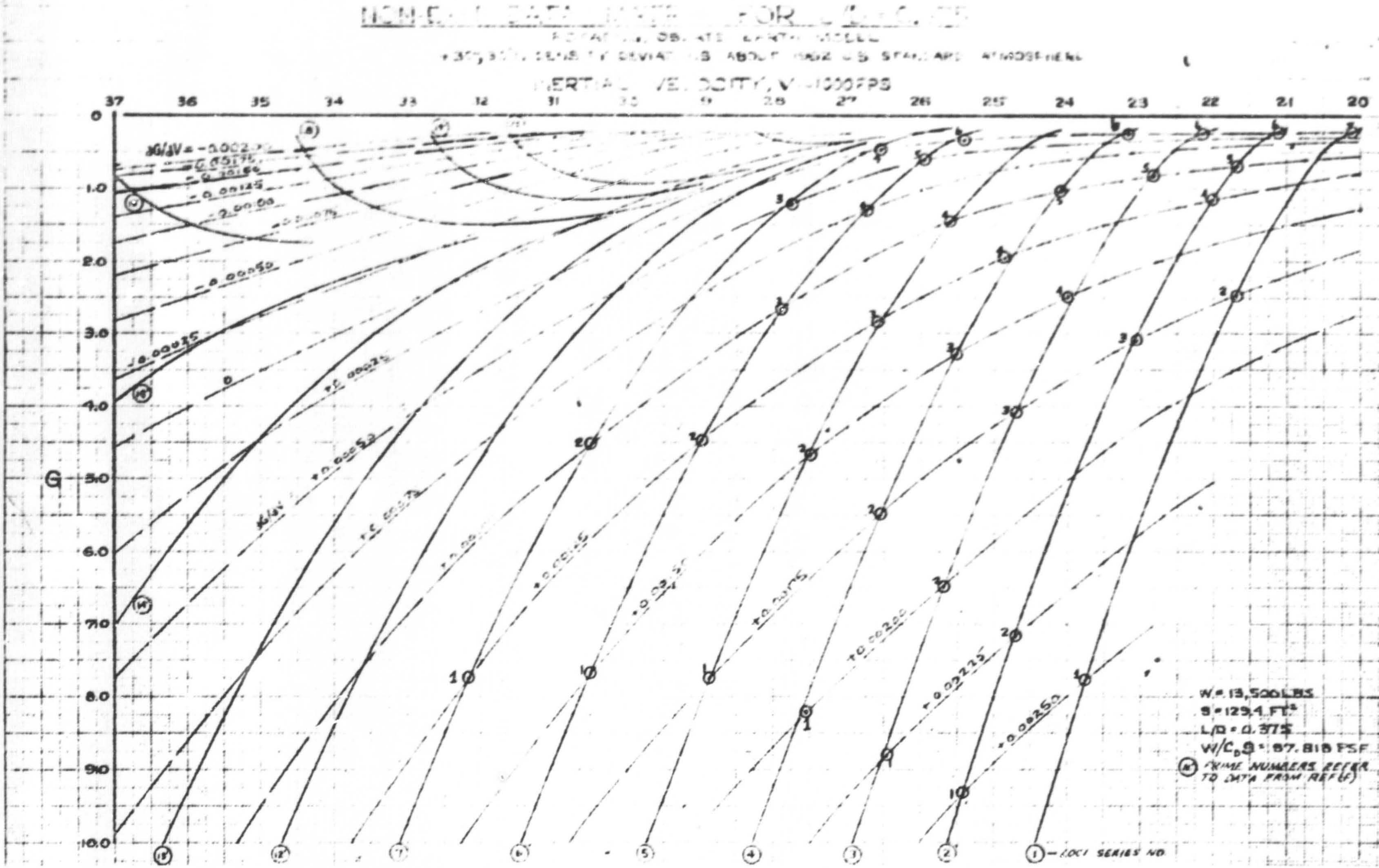


Figure 28(a). - G vs velocity and values of constant dG/dV for loci of skip limiting flight conditions (L/D = 0.375)

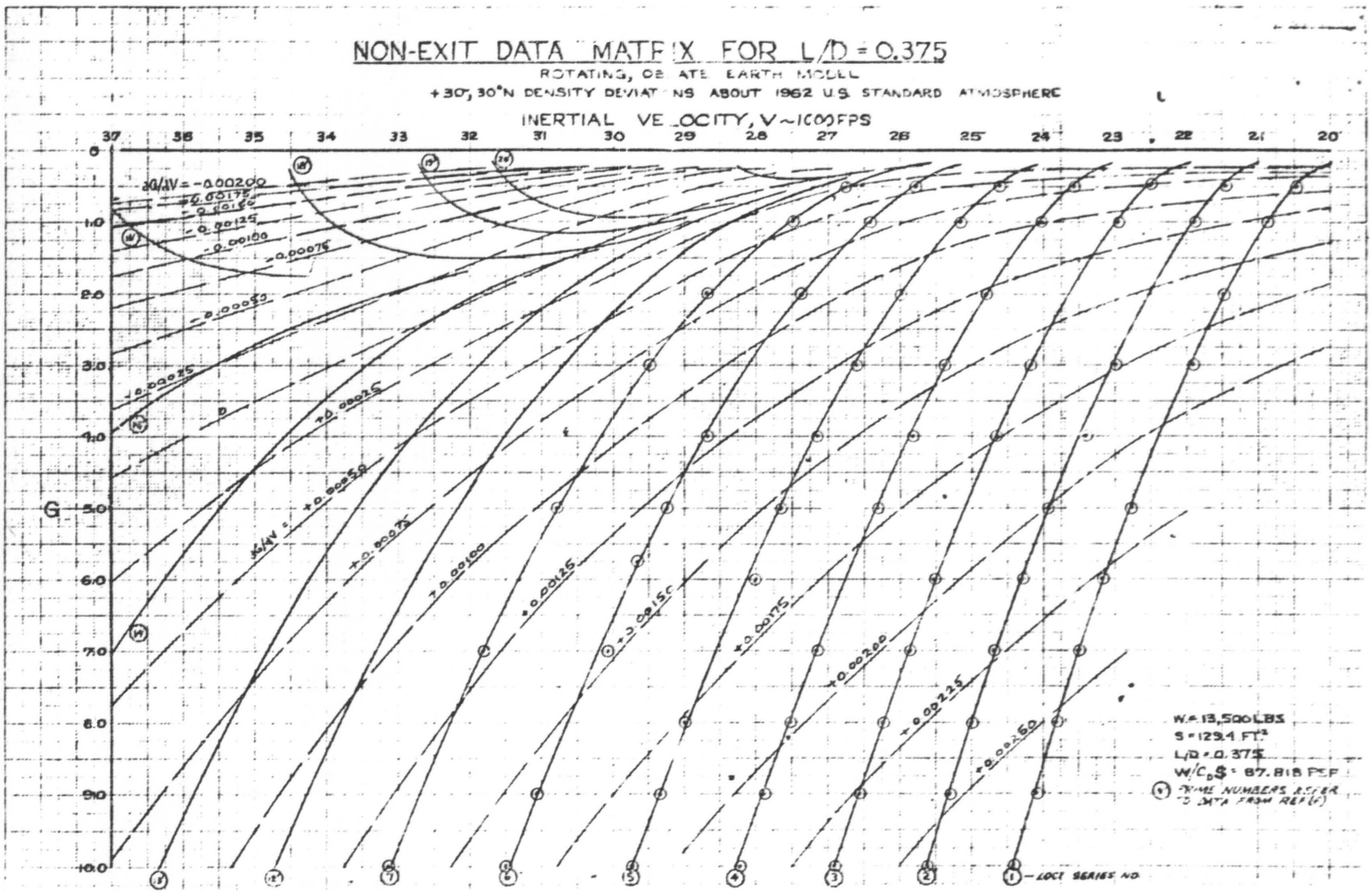


Figure 28(b). - G vs velocity and values of constant dG/dV for loci of skip limiting flight conditions (L/D = 0.375)

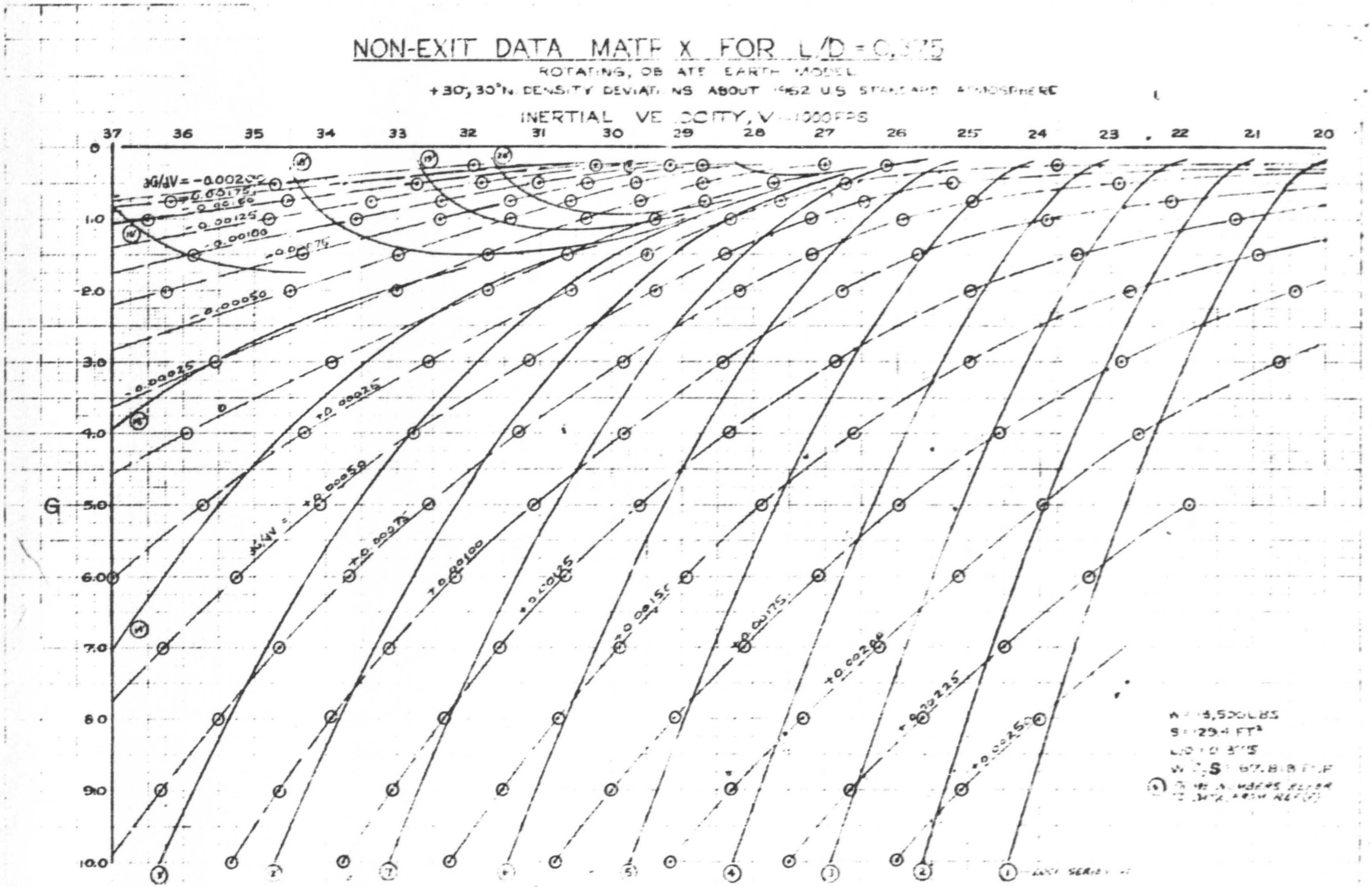


Figure 28(c). - G vs velocity and values of constant dG/dV for loci of skip limiting flight conditions (L/D = 0.375)

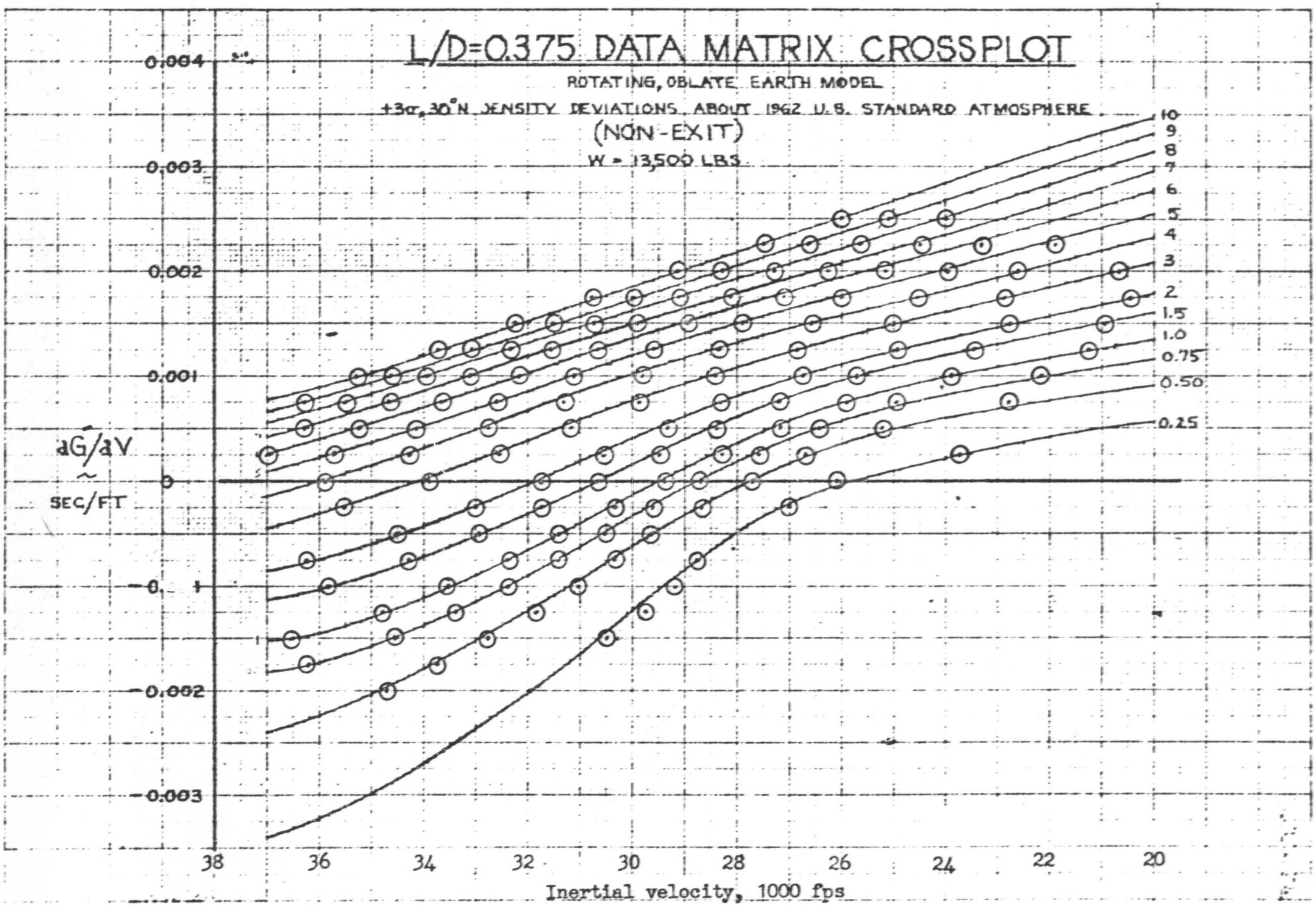


Figure 29. - dG/dV vs velocity for values of constant G (L/D = 0.375)

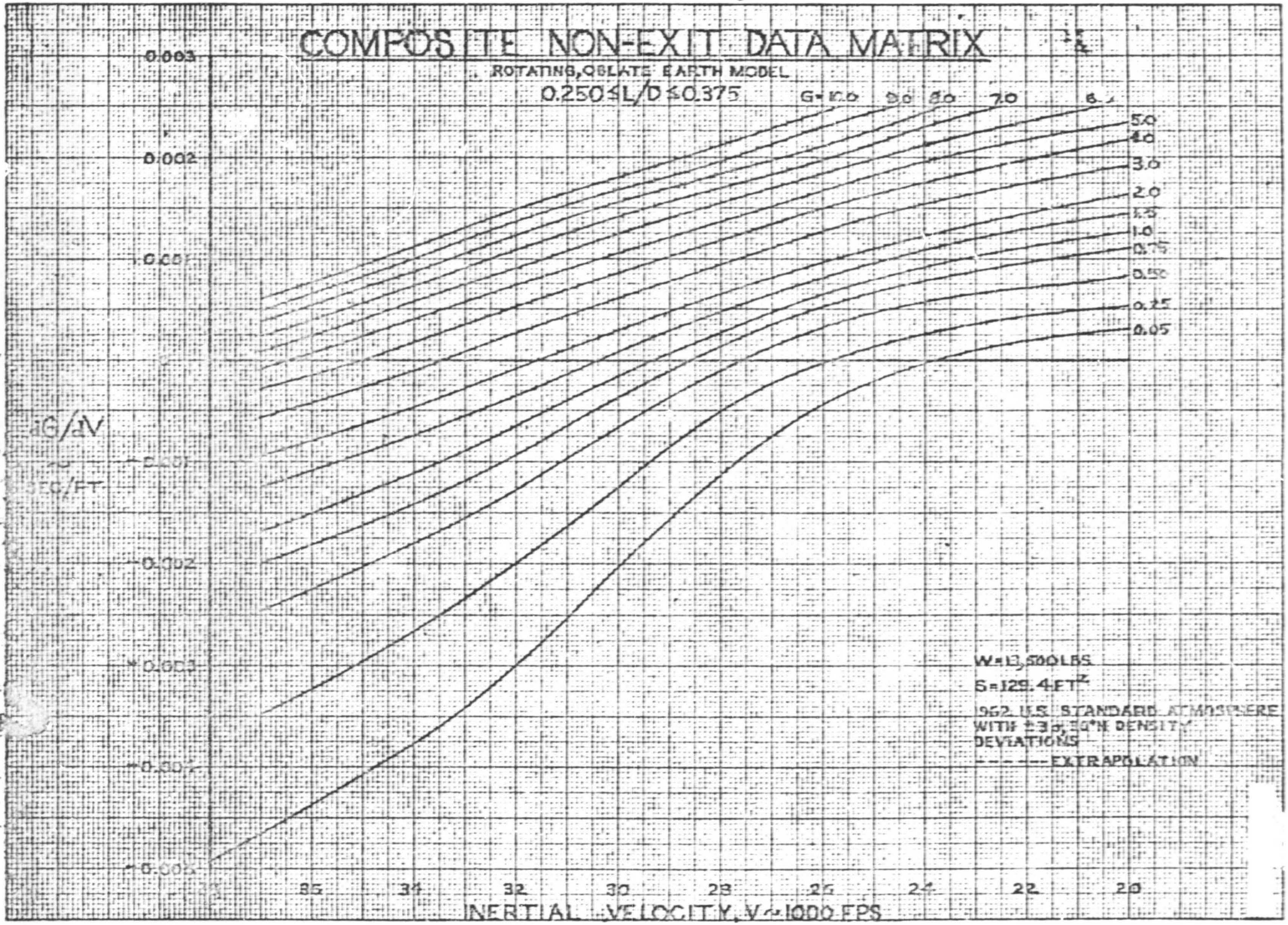


Figure 30. - dG/dV vs velocity for values of constant G ($0.250 \le L/D \le 0.375$)

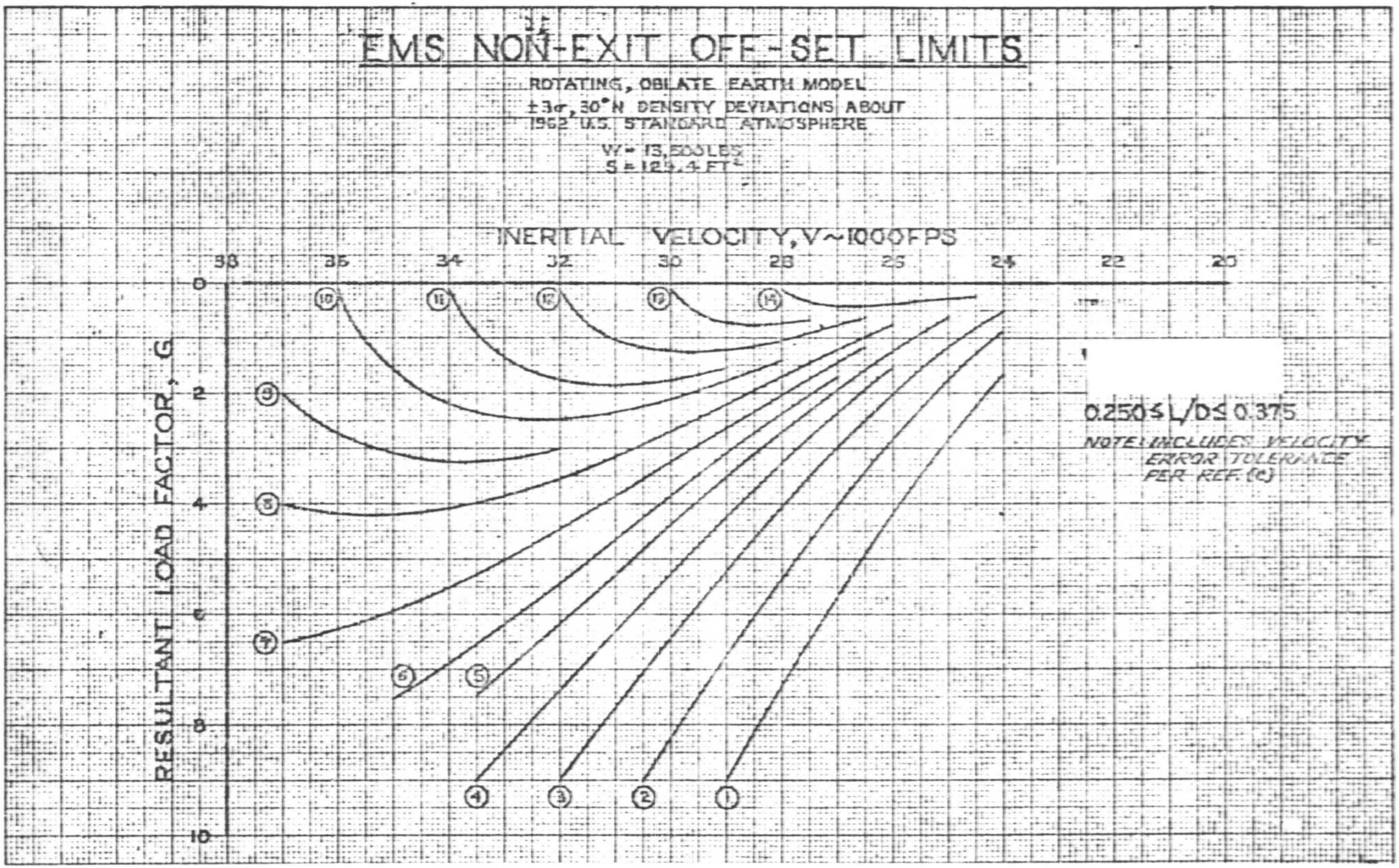


Figure 31. - Final form of skip limit lines displayed by the EMS

NOMINAL 1962 U. S. STANDARD ATMOSPHERE

VEHICLE WEIGHT = 13,500 LBS

L/D = 0.300

ENTRY TRAJECTORY FLOWN FROM EQUATORIAL ORBIT

Figure 32. - Analytical model for the range guidelines

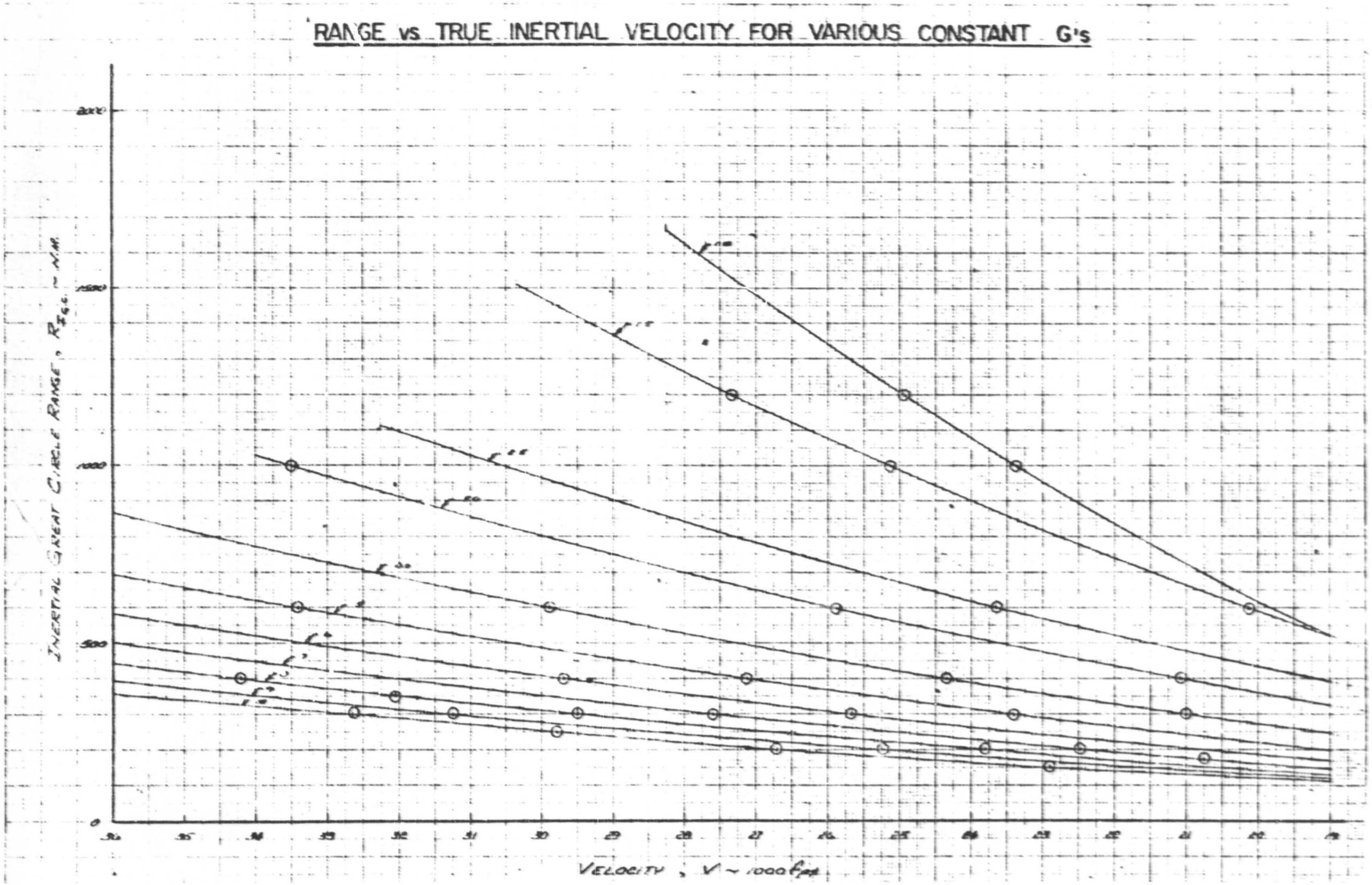


Figure 33(a). - Range vs inertial velocity for values of constant G (L/D = 0.300)

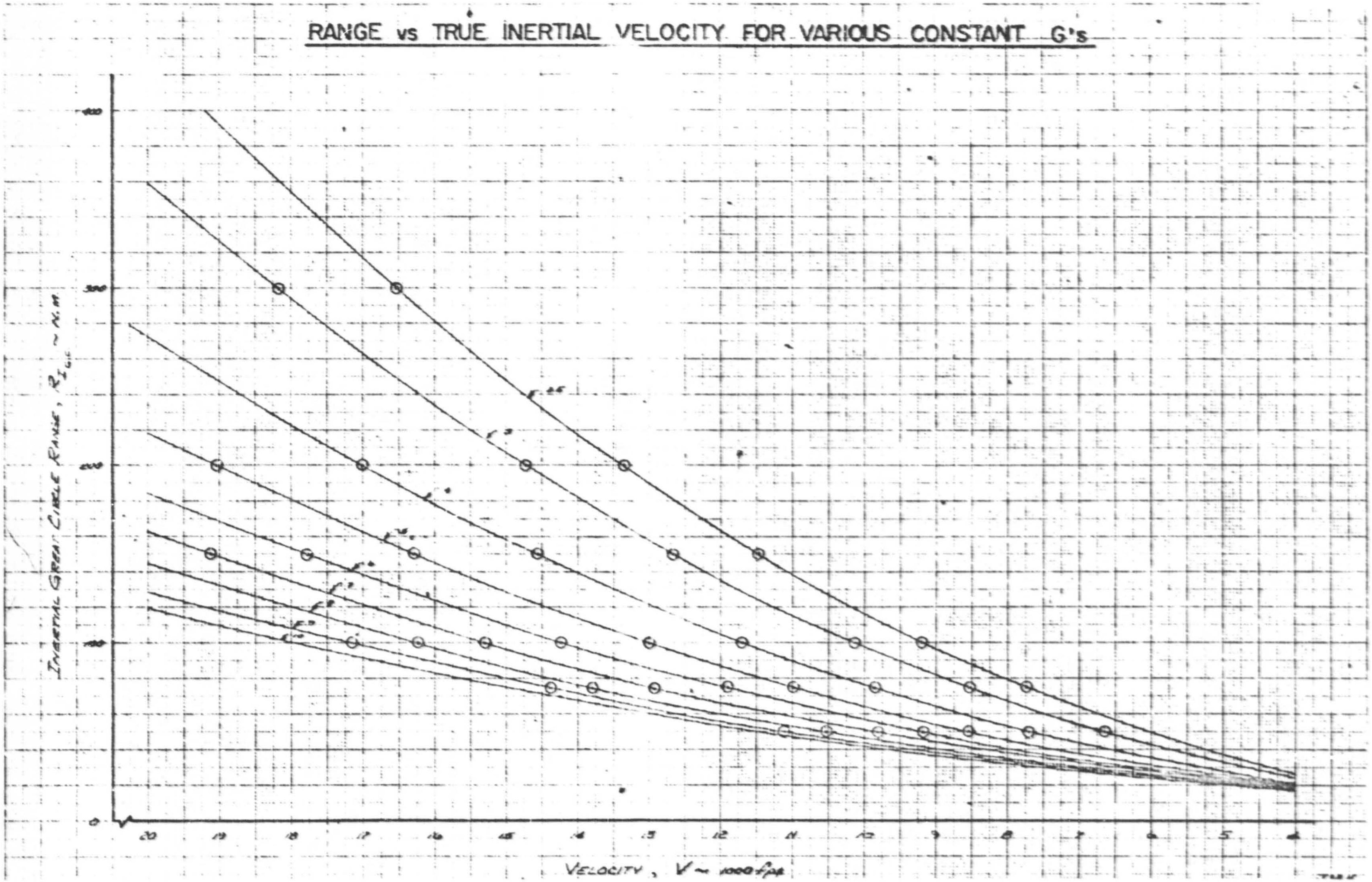


Figure 33(b). - Range vs inertial velocity for values of constant G (L/D = 0.300)

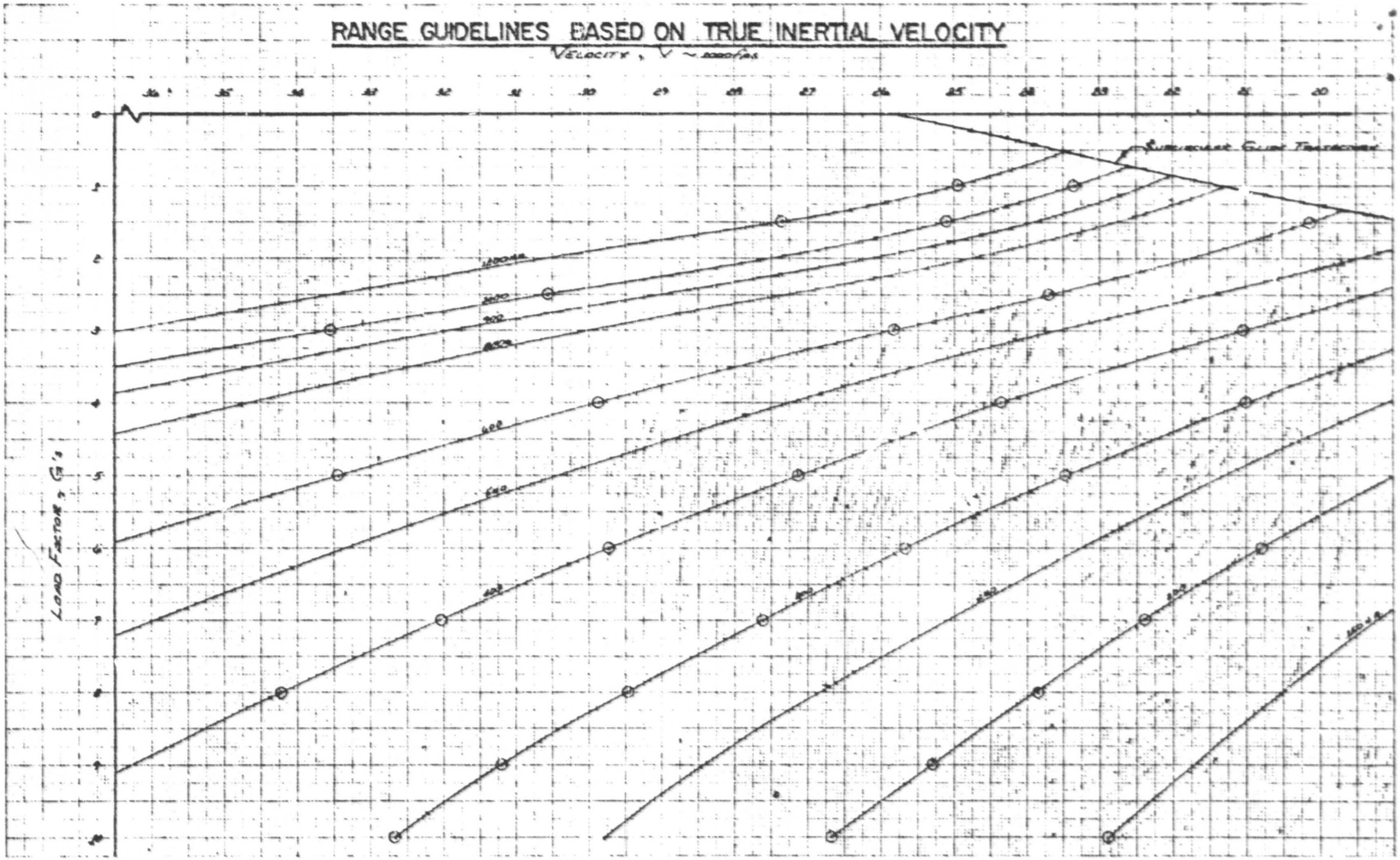


Figure 34(a). - G vs velocity for values of constant range (L/D = 0.300)

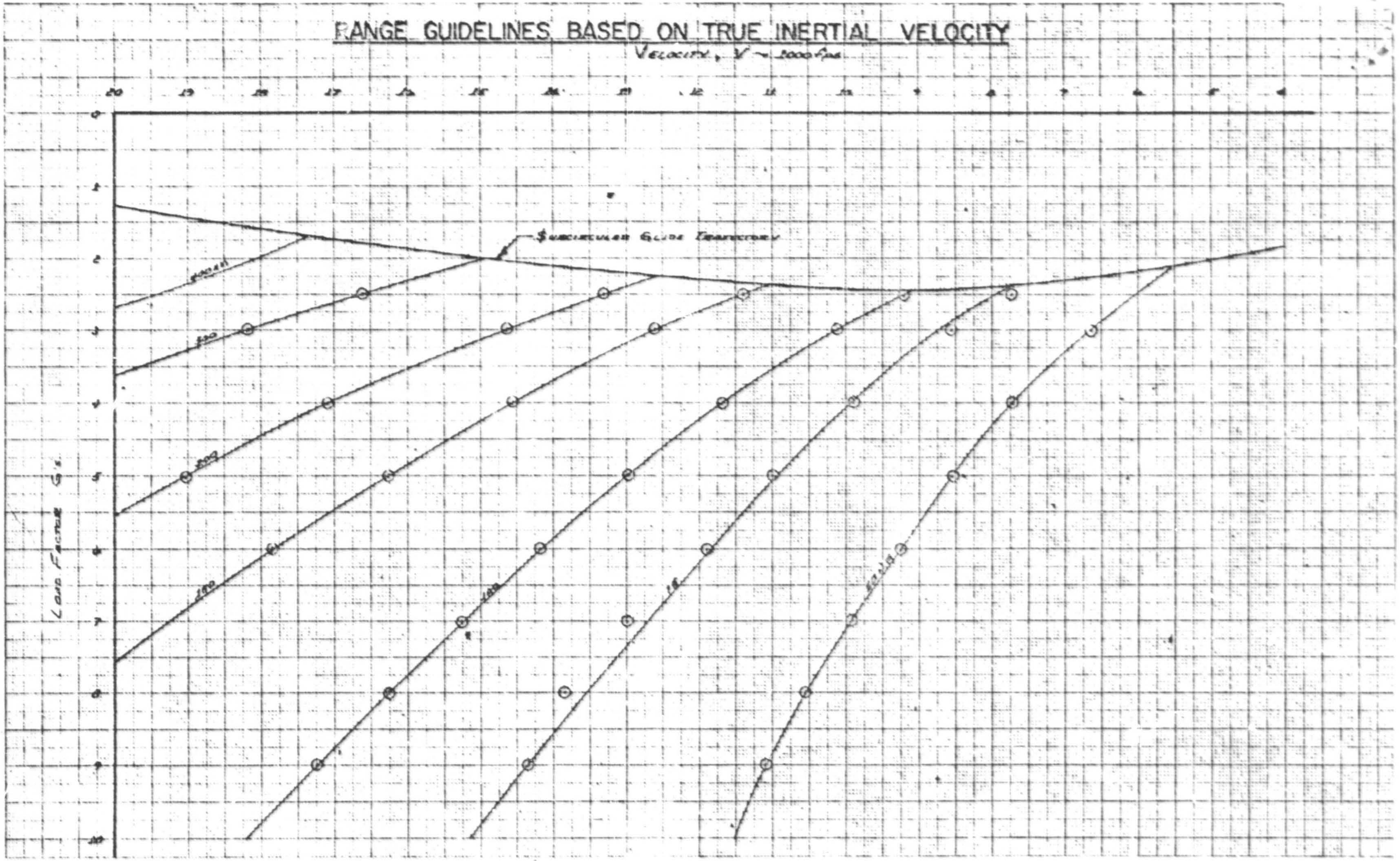


Figure 34(t). - G vs velocity for values of constant range (L/D = 0.300)